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The Impacts of External Nutrient Sources on Marine Phytoplankton in an Eastern Shore Sea-Side Estuary

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by

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ABSTRACT

THE IMPACTS OF EXTERNAL NUTRIENT SOURCES ON
MARINE PHYTOPLANKTON IN AN EASTERN SHORE SEA-SIDE ESTUARY

Claudette Lajoie Jenkins
Old Dominion University, 1999
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The Eastern Shore of Virginia (Greens Creek) as well as a large portion of the North Atlantic coastline is characterized by estuarine systems not dominated by large river systems. Instead, small freshwater creeks influence many coastal systems yet little information has been documented on their ecological significance. The focus of this research is to identify the biogeochemical and physical interactions within an estuarine water-column and understand the importance of freshwater sources in governing phytoplankton production. The hypothesis of this research is that increases in external nutrient loading into Greens Creek will not result in an increase in primary production. The reasons behind this are due to the light limitation of photosynthesis and high tidal exchange rates, removing phytoplankton, in this creek system.

Nutrient concentrations, species composition and nutrient loading rates for reservoir discharge, groundwater and precipitation will be presented. In addition, a rainfall related runoff model was also incorporated into this research to assess the indirect impacts of atmospheric deposition.

This research shows that a total of $1.80(*10^7)$ moles DIN yr^{-1} and $1.72(*10^5)$ moles P yr^{-1} are input to Greens Creek via freshwater sources annually. The continuous freshwater discharge from the reservoir spillway accounts for the majority of the total freshwater DIN (97.5%) and P (97.2%) inputs into Greens Creek. Groundwater discharge and rainfall are believed to be of substantial significance only on shorter time scales. Nutrient data from all input sources indicates that NO_3^- is the dominant form of DIN input to the creek with NH_4^+ and NO_2^- being of less significance.

Evidence shows that Greens Creek phytoplankton are light-limited in the turbid nutrient-rich waters of the upper and mid-reaches of the creek. However, as water becomes clearer downstream in the lower more saline reaches phytoplankton production increases and nutrient concentrations become low. Recharging tides characterized by high tidal energy break down the freshwater stratification and create a well-mixed water-column. This well-mixed environment drastically dilutes nutrient concentrations thus limiting phytoplankton growth. Daily production was strongly correlated with ambient nitrate concentrations and inversely correlated with salinity, emphasizing the importance of freshwater inputs as a nutrient source in this system.

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The Virginia Coast Reserve (USDA SARE Grant awarded to The Nature Conservancy) and the Hampton Roads Scholarship program generously provided financial assistance to support this research. The Department of Ocean, Earth and Atmospheric Sciences at ODU was instrumental in not only providing financial support for this research but also providing endless resource support including computer, boat and transportation facilities.

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To all my family and friends, both new and old, I am grateful for the continuous support and encouragement you have given me to pursue my dreams. May we always have new dreams to aspire and share. Cheers.

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CHAPTER I
INTRODUCTION

Estuaries and their associated marshes are among the most productive of aquatic environments and are viewed as geochemical reaction vessels through which the fluvial flux of continentally weathered solutes and solids must pass to enter the oceans. As a result, complex biological, chemical and physical interactions within the water-column are of great importance to the observed nutrient distributions and phytoplankton community structure within the estuary. Generally, research has been concentrated in large estuaries such as the Delaware and San Francisco Bay, which are dominated by large-scale industrial, municipal and agricultural activities. These large estuaries typically have sizable rivers associated with them supplying tremendous quantities of freshwater to estuarine systems. River flow is typically the primary control of estuarine nutrient variability on both a seasonal and interannual time-scale; therefore, upstream river characteristics have important consequences on the health of the downstream estuarine environment.

In coastal embayments not dominated by rivers, small freshwater creeks influenced by groundwater discharge and episodic precipitation are the primary means by which nutrients and freshwater are loaded into the system. These small groundwater driven estuarine ecosystems are common features of the Northeastern United States and differ from their counterparts dominated by large rivers yet little information has been documented on their potential ecological significance. A key focus of this research is to investigate the hydrologically linked terrestrial and marine ecosystems of the Eastern Shore and understand the impact that upland agricultural practices have on this estuarine system. To date, few studies have addressed groundwater as a major transportation mechanism of nutrients to the Eastern Shore coastal environment and the relevance of this advective freshwater movement from groundwater driven creeks in regulating the surrounding marsh-estuarine productivity.

The journal entitled *Estuaries* was used as a model for this publication.

Statement of the Hypothesis

The hypothesis of this research is that increases in external nutrient loading into Greens Creek will not result in an increase in primary production due to a combination of intense light limitations and high tidal exchange rates in this creek system. Based on this hypothesis; the following research objectives were addressed:

1. Nutrient Concentrations - Nutrient concentrations were determined for all freshwater nutrient sources to Greens Creek, which are primarily due to precipitation and groundwater. Nutrient concentrations were also determined at various locations within the creek in order to determine the significance of dissolved nutrient concentrations available for phytoplankton uptake. In addition, the results of this information will provide valuable insight regarding Greens Creek as an exporter of nutrients and production to the adjacent coastal lagoon.
2. Chlorophyll-a Concentrations - Measurements of the phytoplankton pigment chlorophyll-a were determined at various locations within Greens Creek to not only quantify phytoplankton biomass but also act as indicator of phytoplankton health. Chlorophyll-a is also an important measure of light availability and provides a useful survey of primary production.
3. Water Column Exchange - The intensity of water column exchange occurring within Greens Creek is an important factor that may play a large role in controlling phytoplankton production. It is important to correlate exchange intensity with the growth rates of the phytoplankton species present in order to gain insight on the possible physical factors controlling phytoplankton production.

The following sections describe in detail both the research objectives presented here and the methods chosen to prove this hypothesis.

The main focus of this research is to investigate the hydrologically linked terrestrial and marine ecosystems of the Eastern Shore and understand the impact that upland agriculture practices have on the Greens Creek estuarine system. The overall objectives for this study are:

(1) To quantify atmospheric loading rates and determine the importance of atmospheric deposition as a nutrient source for the nearshore phytoplankton community.
(2) To quantitatively and qualitatively describe groundwater as the hydrologic link between the terrestrial and marine environment.
(3) To understand the ecological significance of this nutrient-rich freshwater movement into Greens Creek and examine the behavior of dissolved nutrients associated with that flow.
(4) To evaluate the impact of nutrient rich freshwater on the phytoplankton community and the role phytoplankton have on the speciation of the water-column nutrients.

To accomplish these objectives, a field approach was utilized over a three year study period. Many analytical water quality techniques in conjunction with a variety of mathematical equations were employed to obtain the quantitative information. In the following sections, detailed descriptions of the proposed research are given, and when appropriate, more specific questions and the approaches to answering them are described.

Implications of Research

The Eastern Shore of Virginia is characterized as a narrow peninsula with prime agricultural soils between the Atlantic Ocean and the Chesapeake Bay. This land has a long history of low intensity human uses and a human population with a great awareness of the land, water, and other natural resources that this system offers. Research on the Eastern Shore has generally focused on the bay-side of the peninsula and the many interactions that occur within the Chesapeake Bay estuarine system. Due to the lack of well documented research on the sea-side ecosystems on the Eastern Shore, there are many unanswered questions regarding the health of these systems. In addition, even less information is understood about how these nearshore environments interact and influence the coastal ocean.

The Eastern Shore as well as a large portion of the North Atlantic coastline is characterized by estuarine systems not dominated by large river systems. A primary focus of this research is to identify the complex biogeochemical and physical interactions within an estuarine water-column and understand the importance of freshwater sources in governing phytoplankton production. The primary sources of freshwater to these systems are via groundwater and precipitation events, both of which can potentially supply tremendous concentrations of continentally weathered solutes and solids. The flux of chemicals, nutrients, and particulate matter greatly impact the complex biological interactions within the estuarine water column.

Groundwater inputs to estuarine systems are an important environmental factor in many coastal regions of the world. Groundwater not only serves as a major pathway by which freshwater is transported to the sea but is also a principal mechanism by which nutrients, sediments or other chemicals flux directly from the terrestrial to the marine environment. Strong evidence that implicates groundwater as a significant source of nitrogen from the terrestrial to the marine environment, provide compelling reasons to study it as a hydrologic link between ecosystems. Added benefits to studying groundwater are the global need to expand our knowledge of coastal groundwater fluxes and their impact on nutrient behaviors within estuaries as well as developing better groundwater assessment methods. Precipitation's dual role as both a direct source of nitrogen and phosphorus to an ecosystem and a controlling factor in groundwater recharge are compelling arguments why it must be examined in conjunction with groundwater studies. It is extremely important to understand the processes controlling the behavior of these external nutrient sources once in the estuarine system since the impact is of potential ecological importance to the phytoplankton community.

This research, completed in conjunction with the southern region Sustainable Agriculture Research and Education (SARE) program grant awarded to the Nature Conservancy, will assist growers in their transition to sustainable agriculture by developing sustainable technologies and best management practices to preserve the water quality of the surrounding marsh-estuarine environment. In addition, the Eastern Shore also relies heavily on aquaculture and fisheries harvests; therefore, phytoplankton populations represent a significant food resource making it an important commodity

within this system. Ultimately, this research hopes to better understand the hydrologically-linked terrestrial and marine ecosystems in order to assess the impact that upland agriculture practices have on marine algal production. The information gained about the many interactions of Greens Creek, the focus of this research, will not only benefit this single location but also provide valuable insight into assessing the health of the many similar ecosystems on the eastern seaboard.

Study Site

Greens Creek (Fig. 1), on Virginia's Eastern Shore, is a sea-side coastal watershed associated with a mosaic of landscapes including upland agricultural activities, a wetland/hammock area and a coastal lagoon system with free exchange to the sea through a tidal inlet between coastal barrier islands. Greens Creek is a first-order stream of the Machipongo River and discharges directly into Hog Island Bay. The Greens Creek estuary is a tide-dominated barrier island system illustrated by the shore-parallel trends of the backbarrier lagoon and barrier island system (Oertel, 1985). Greens Creek has a terrestrial component (watershed area is approximately 820 ha) comprised of upland agricultural activities at its head, yet is surrounded by extensive undeveloped tidally influenced wetlands (approximately 160 ha) with a long history of low intensity human uses.

The main trunk of Greens Creek is approximately two kilometers long with a maximum cross sectional area of approximately 205 square meters. Figure 1 displays how this creek essentially divides through the agricultural landscape allowing it to act as a conduit for the movement of freshwater, nutrients, sediments or other chemicals directly from the terrestrial to the marine environment. A reservoir is located at the head of Greens Creek and serves as a collector of freshwater stream flow and rainfall comprised of dissolved constituents that are generated directly from upland agricultural activities. Groundwater contributes nutrients to the marine portion of Greens Creek through two primary sources: (1) sub-surface flow due to the shallow groundwater table discharge through the creek banks and (2) in the upland, Greens Creek is a naturally driven groundwater system and enters the marine ecosystem at the reservoir spillway. In

order to evaluate the sub-surface flow that discharges perpendicular to the creek there is a series of three shallow groundwater wells located adjacent to the marsh land of Greens Creek. These wells were monitored on the same sampling schedule as the water column stations.

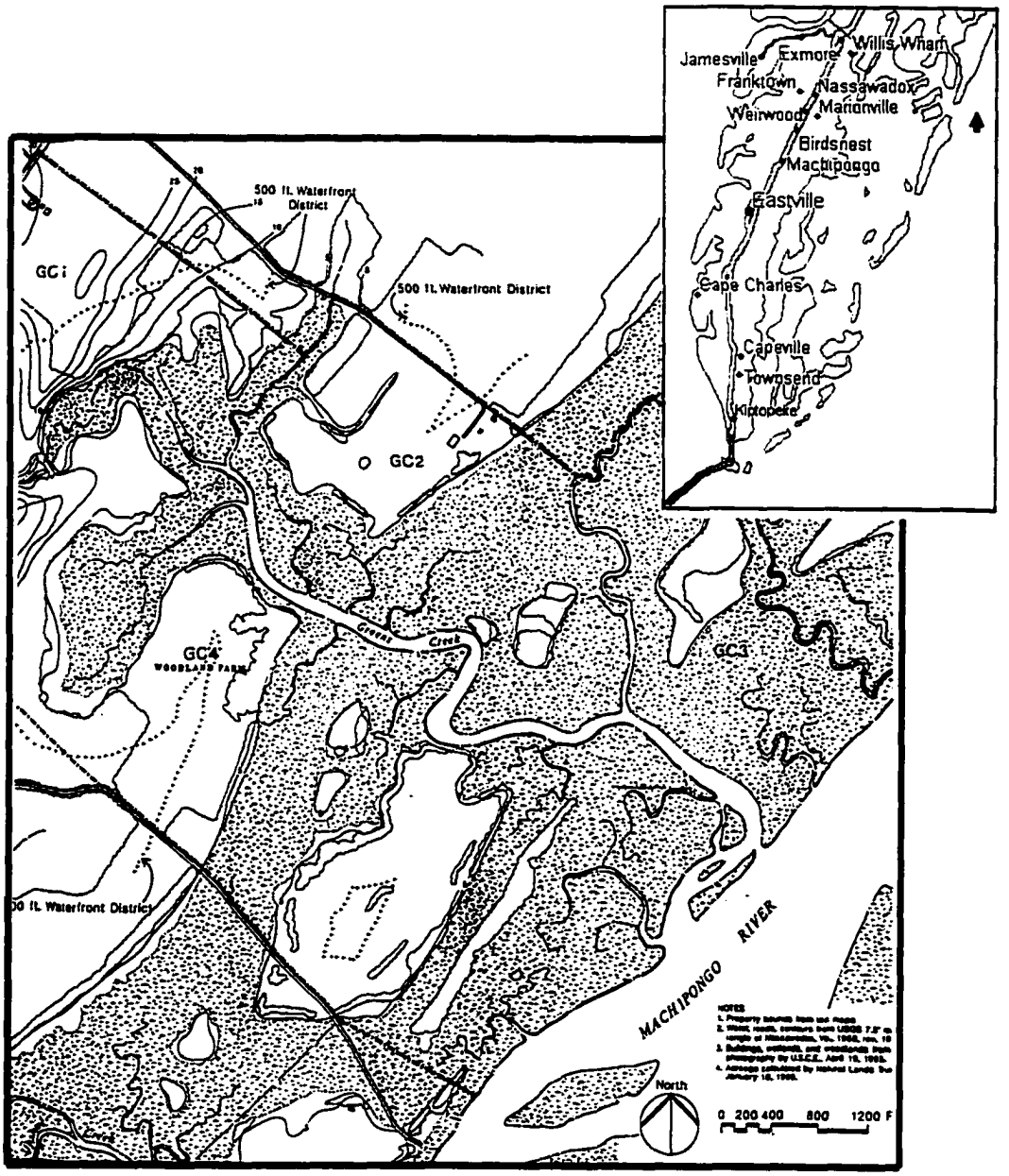

Fig. 1. Large scale and small scale (inset) views of the Greens Creek watershed research site and surrounding coastal environment.

The Greens Creek water column stations transect consisted of one station at the reservoir spillway, four stations within Greens Creek of varying salinity and one station outside of the creek in the Machipongo River (Fig. 2). Creek sampling utilized the Old Dominion University Department of Ocean, Earth and Atmospheric Sciences boat facilities (ODU 1 and ODU 3) to collect all water samples. Surface water samples were collected at all stations in order to document the buoyant freshwater discharge from the upland reservoir to quantify the external nutrient loading from freshwater sources. In a system as dynamic as this one, sampling during ebbing tides compared to flooding tides is critical. All sampling occurred during ebbing tides since this is when the nutrient signal is most evident; whereas, during flooding tides nutrient concentrations become diluted by the inflow of seawater.

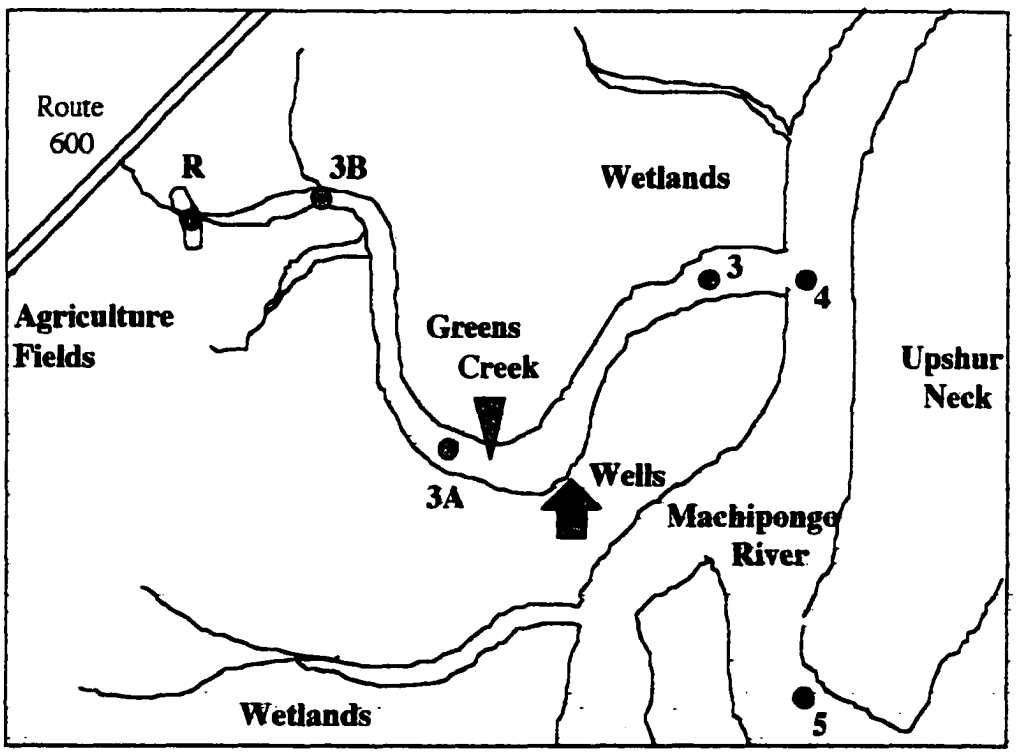

Fig. 2. Station locations for the Greens Creek transect and surrounding environment.

In order to measure the nutrient concentrations of rainfall events and maintain an accurate record of these events, precipitation research was conducted in extensive collaboration with the Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, Virginia (approximately 10 miles from the study site). At this site there is a monitored NOAA Climate and Weather Station where records of daily rainfall and climate data are continuously collected with a standard weather bureau manual rain gauge.

Field Studies and Timing

The key aspects of this research are (1) to determine the concentrations and fates of nutrients entering the estuary from several sources within the watershed, (2) to compare the uptake and transformation of nutrients in the estuary to the rates of input from the watershed and (3) to evaluate the impact of these nutrient inputs on the marine algal community of the estuary. This research focuses on seasonal changes, spatial patterns, and fluxes of nutrients and chlorophyll concentrations that occur in Greens Creek. Ultimately, the purpose of this research is to be able to both quantitatively and qualitatively describe how N, P and silicate fluxes from the watershed are altered in transit through Greens Creek to the coastal lagoon. To accomplish these goals, a field approach (Table 1) was utilized over a three-year study period (field sampling and analysis in Years 1 and 2 and completion of data analysis and interpretations in Year 3).

TABLE 1. Field scheduling of all environmental parameters investigated for this research.

PARAMETER	SAMPLING PERIODS	ANALYSIS
Precipitation	October 1996-1998	nitrate, nitrite, ammonium, phosphate deposition rates

TABLE 1 Continued.

PARAMETER	SAMPLING PERIODS	ANALYSIS
		loading rates
Shallow Groundwater	May 1996-1998	nitrate, nitrite, ammonium, phosphate salinity discharge rates
Creek Water Quality		
Nutrients	May 1996-1998	nitrate, nitrite, ammonium, phosphate, silicate
Temperature	May 1996-1998	temperature gradients
Salinity	May 1996-1998	salinity gradients
Light (PAR)	May 1996-1998	Photosynthetically Active Radiation light gradients
Phytoplankton		
Biomass	May 1996-1998	size fractionated chl-a species identifications
Productivity	variable	primary production
Zooplankton	Sept.1997-May 1998	biomass species identifications

Table 1 concisely lists the field scheduling of all environmental parameters encompassed in this study including precipitation analysis, shallow sub-surface groundwater analysis, and creek water quality.

Methods and Procedures

Precipitation Nutrient Analysis

In order to measure the nutrient concentrations of rainfall events and maintain an accurate record of these events, samples were collected at the Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, Virginia (approximately 10 miles from the study site) as previously described. For the purposes of this research, an event was defined as a weather system that yielded at least 0.25 inches of rain in the collector. Samples were collected in preconditioned HDPE bottles and stored at –18 °C in the freezer at ESAREC until transport to the laboratory where they were filtered through Whatman GF/F glass-fiber filters and stored frozen until analysis. Replicate analyses of phosphate, nitrate, nitrite and ammonium were determined for each rain sample using standard colorimetric methods (Parsons et al., 1984): [NO_3^-] were analyzed by running samples through columns filled with cadmium fillings coated with metallic copper; [PO_4^{3-}] were analyzed by allowing samples to react with a molybdic acid, ascorbic acid and trivalent antimony reagent; [SiO_2] were analyzed by allowing samples to react with molybdate; [NH_4^+] were analyzed in samples by treating them in an alkaline citrate medium with sodium hypochlorite and phenol in the presence of sodium nitroprusside; and [NO_2^-] was analyzed by allowing samples to react with sulfanilimide in an acid solution. As a result of this analyses, concentrations of nutrient species were multiplied by rainfall volume to estimate precipitation loading rates (mg m^{-2} $time^{-1}$) on both a per event and yearly basis. Precipitation data may aid in the delineation between wet and dry seasonal conditions during the year and thus yield valuable insight on the observed salinity concentrations within Greens Creek. The main goal of this section of the research is not only to define the quantity of atmospheric deposition but to also investigate the bioavailability of rainfall as a nutrient source for coastal phytoplankton.

Rainfall Runoff Model

In addition to describing the nutrient composition of precipitation events in the Greens Creek watershed, a nonpoint source runoff model was also incorporated into this

research. Nonpoint source pollution, including rainfall-related runoff, may contribute a significant amount of biologically available nutrients to the coastal environment. The volume and composition of rainfall related runoff is primarily characterized by the land use types characteristic of the watershed. The basis of the model used for this research was adopted from a model developed by Wong et al. (1997) for the Santa Monica Bay watershed. The key focus of the model is to determine the overall average storm runoff volume relative to rainfall volume for a particular watershed. Wong et al. (1997) have shown that the runoff coefficient (RV) (eqn. 1) is defined as the overall average ratio of runoff to rainfall and is highly correlated to the impervious surface area (IMP) of a watershed according to the following equation:

$$RV = 0.007\ IMP + 0.1 \qquad \text{(eqn. 1)}$$

where IMP is expressed as a percentage based on a given land use category for the watershed (Table 2). Once the runoff coefficient is determined for the watershed, the average storm runoff volume (ASV) (eqn. 2) can be calculated from the following equation:

$$ASV\ (m^3) = RV * area * CF * ASRF \qquad \text{(eqn. 2)}$$

where RV is the runoff coefficient; area is the area of the catchment (m^2); CF is the rainfall correction factor; and ASRF is the average storm rainfall for the catchment (m). The annual average storm runoff (AASV) (eqn. 3) is simply

$$AASV\ (m^3\ year^{-1}) = ASV * NSTORM \qquad \text{(eqn.3)}$$

where NSTORM is the average number of storms per year. All parameters needed in this model were determined from the daily rainfall records maintained by the Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, Virginia.

TABLE 2. Impervious surface area (IMP) values for corresponding land use characteristics. (Values based on Los Angeles County Department of Public Works, NPDES Permit No.CA0061654, Attachment 1, Santa Monica Drainage Basin, Drainage Area Characterization) (Wong et al., 1997).

Land Use Category	Impervious surface area
Single family	42
Multifamily	68
Commercial	92
Public	80
Light industrial	91
Other urban	80
Open	0
Unknown	65

Groundwater Nutrient Analysis

In order to evaluate the sub-surface discharge which flows perpendicular to the creek three shallow groundwater wells adjacent to the marsh land of Greens Creek were monitored. These wells were monitored on the same sampling schedule as the water column stations since discharge rates are greatest during periods of ebbing tides which allows the freshwater nutrient signal to be most evident. Nutrient samples from all shallow groundwater wells were collected using a vacuum hand-pump (<15 pounds per square inch) and stored in preconditioned (acid-cleaned) HDPE bottles. All samples were stored on ice until returning to the laboratory for processing.

On returning to the lab, 250-ml aliquots from the HDPE nutrient sample bottles were processed for future dissolved nutrient analysis. Samples were filtered through Whatman GF/F glass-fiber filters under pressure less than 5 pounds per square inch. Filtrates were immediately frozen as to retard any chemical reactions until later analysis. Analyses of phosphate, nitrate, nitrite and ammonium were performed on all groundwater

samples according to the previously described standard colorimetric methods of Parsons et al. (1984) scaled down to 25-ml portions for remaining analyses of phosphate, nitrate, nitrite and ammonium. All nutrient samples were measured in replicate as to ensure the statistical significance of the method.

Freshwater discharge rates were calculated for sub-surface shallow groundwater flow into Greens Creek. In order to calculate freshwater discharge rates of the sub-surface shallow groundwater measured in the three wells, a rate of flow equaled to 2.0 L m^{-2} hr^{-1} (Robinson et al., 1997) based on an extensive literature review on the Eastern Shore was used. Discharge rates in conjunction with nutrient measurements will allow for the comparison of the Greens Creek system with large river systems to determine if small freshwater creeks may input equivalent concentrations of nutrients as large rivers on a per volume basis.

Water Quality Nutrient Analysis

The Greens Creek water quality transect consists of one station at the reservoir spillway (Station R), four stations within Greens Creek of varying salinity (Stations 3B, 3A, 3 and 4 in order of increasing salinity) and one station outside of the creek (Station 5) in the Machipongo River (Fig. 2). Surface water samples were collected at all stations to document the buoyant freshwater discharge from the upland reservoir in order to quantify the external nutrient loading from groundwater and to interpret water quality conditions. Nutrient samples on this transect were collected in preconditioned (acid-cleaned) HDPE bottles and stored on ice until returning to the laboratory for processing. Samples for phytoplankton species identification and pigment analysis were also collected using 4L LPDE polycarbonate cubiecontainers and stored on ice until returning to the lab for processing. Hydrographic data such as temperature, salinity and light transmission were measured at the time samples were collected using a YSI 30 Salinity, Conductivity, Temperature Probe and a Li-Cor, Inc. Quantum /Radiometer / Photometer.

On returning to the lab, 250-ml aliquots from the HDPE nutrient sample bottles were processed for dissolved nutrient analysis using the same technique previously described for the groundwater samples. Analyses of silicate, phosphate, nitrate, nitrite

and ammonium were performed in replicate according to the previously described standard colorimetric methods of Parsons et al. (1984).

Much of the water quality data was interpreted using property-property plots (Fig. 3) in which a known chemically conservative property such as salinity is plotted against a constituent of interest (i.e. nutrient concentration) (Kaul and Froelich, 1984). These property-salinity plots allow researchers to better understand the behavior of nutrients within the water-column as well as those processes that regulate the input, removal and recycling of these nutrients within an estuarine system. By examining such plots, three mixing patterns become apparent: linear (conservative), convex upward (in situ production) and concave upward (in situ removal). Results and interpretations based on this approach were viewed cautiously due to the complex hydrodynamic processes occurring and the variations in both fresh and saltwater endmember dissolved constituent concentrations. This method provides a valuable assessment tool to understand the processes characterizing the upstream terrestrial dynamics in order to understand the downstream estuarine variability. All nutrient samples were measured in replicate as previously described so that statistical means and standard errors could be determined for this research.

Phytoplankton Quantification

Surface water samples (approximately at 0.3 m depth) were collected in five-liter cubiecontainers for phytoplankton investigations. Phytoplankton biomass was quantified by determining concentrations of photopigments, specifically chlorophyll-*a* and phaeopigment-*a*, in the natural samples. Size-fractionated chlorophyll-*a* samples for total population and <20-μm fractions were filtered through Whatman GF/F glass-fiber filters (under less than 5 psi). The filters were folded, placed in polyethylene vials and immediately frozen. Photopigment concentrations were determined fluorometrically using the tissue grinding method based on the technique by Yentsch and Menzel (1963) and revised by Holm-Hansen et al. (1965). This method requires that algal cells concentrated on filters be extracted in 90% acetone following mechanical disruption of the cells. Phytoplankton pigment samples were done in triplicate and analyzed using a

Turner 10-AU Fluorometer. Pigment concentrations at each station were also grossly correlated with both phytoplankton cell number and species identification.

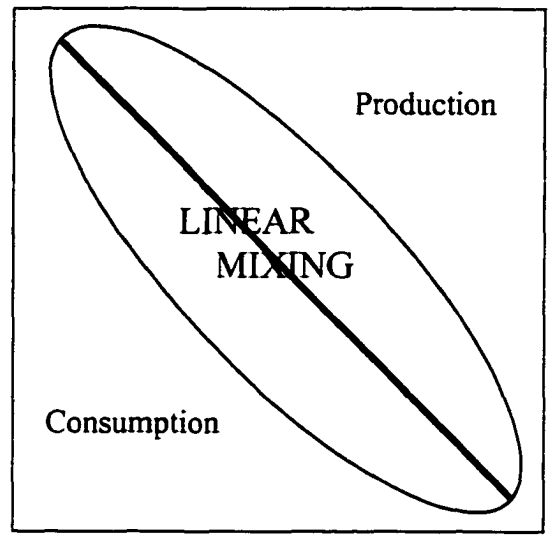

Fig. 3. Conceptual diagram of the three possible mixing patterns associated with property-property plots.

Natural population samples were preserved in Lugols for determining species abundance and identification using a Zeiss inverted microscope. Natural population samples from each station were shaken and settled in 10mL chambers overnight for enumeration the following day. Phytoplankton species enumeration was quantified by first scanning the entire slide on 400X magnification to count the larger species contained within the sample. Second, species were identified and counted on 200X magnification by scanning a maximum of 9 fields or a total of 100 cells on the slide. Chain forming species were counted by the number of single cells composing the chain. Cyanobacteria cell counts and identifications were excluded from this research since cyanobacteria are adversely affected by the strong turbulent conditions which characterize this estuarine system. Cell counts were reported as the number of cells per liter.

Among the numerous methods developed for measuring the primary production of phytoplankton in terms of carbon, the use of tracers such as ^{14}C incorporated with the light-dark bottle technique have largely predominated since its introduction by Nielsen (1952). For this field study, production estimates were determined at various times throughout the sampling period. Incubation bottles were filtered at time = 0 and at the end of the experiment through 25mm Whatman GF/F glass fiber filters. Filters were placed in 20mL glass scintillation vials and transported back to the laboratory where they were prepared for radiocarbon counting. On returning to the lab, filters were allowed to dry overnight to ensure the complete removal of unfixed inorganic ^{14}C. A 15mL aliquot of liquid scintillation media (Aquasol) was added to each of the samples and counted for 4 minutes in a Packard Tri-Carb 2000 CA Liquid Scintillation Analyzer. The Packard analyzer uses a propriety method to mathematically transform the raw Compton spectrum generated in the scintillation cocktail by an external source. This procedure minimizes distortions due to wall and volume dependent effects that can vary from sample to sample. Rates of production were determined using the following equation:

$$\text{Production (mg C m}^{-3}\text{ day}^{-1}) = [((\text{CPM}*\text{BF})/\text{Total CPM}) * W * D]/T \qquad \text{(eqn.4)}$$

where

CPM	= counts per minute of sample
BF	= a calculated bottle factor
Total CPM	= total counts per minute added
W	= estimated mass of carbon in seawater (24,000 mg C m^{-3})
D	= ^{12}C to ^{14}C diffusive rate of plant uptake
T	= incubation time (hours)

In addition to the traditional ^{14}C method, primary production estimates were also modeled with monthly biomass and light measurements in order to determine monthly production estimates. The premise of this model is based on the idea that short term, or instantaneous, depth integrated primary production can be estimated very well by three factors: phytoplankton abundance, depth of the photic zone and the amount of incident light (Hinga et al., 1995). Primary production estimates can then be derived from the following equation (eqn. 5):

$$\text{Primary Production (P) (mg C m}^{-2}\text{ day}^{-1}) = B * Z_p * I_o \qquad \text{(eqn. 5)}$$

where B = phytoplankton abundance measured as chlorophyll *a* (mg chl-*a* m^{-3})

Z_p = photic depth (m)

I_o = surface irradiance (360° sensor) (E m^{-2} day^{-1})

Zooplankton grazing may be a primary control on phytoplankton biomass; therefore, zooplankton biomass estimations were also determined for Greens Creek. Oblique plankton tows were taken in the main stem of Greens Creek near station 3 between September 1997 and May 1998. All plankton tows were collected with a conical plankton net (242 μm mesh) and calibrated flow meter. Tows were conducted in triplicate. Zooplankton samples were preserved in the field using a 10% formalin solution until biomass estimates and species identifications were determined. At the time of identification, samples were washed and stored in a 70% isopropyl solution. Samples were identified according to taxonomic levels in order to estimate biomass. In cases where plankton samples had dense volumes, they were split using a Folsom Plankton Splitter. This apparatus allows the sample to be repeatedly sub-divided into equal parts for ease of counting and identification. All samples were analyzed on an Olympus SZH-10 Compound Microscope Image Analysis system in conjunction with a 486 Targa Frame Grabber and Sigma-Scan Pro 2.0 image analysis software. Plankton densities are expressed as number of animals per liter.

Physical Parameters

Hydraulic turn-over time (HTT) is defined as the time it takes to exchange all of the water in a basin under the assumption that there is complete mixing of the incoming water with the receiving water before exiting. HTT (eqn. 6) is related to 1.) inflow sources into the basin; 2.) outflow sources; and 3.) capacity of the basin (Kjerve and Magill, 1989). Greens Creek has multiple inflow sources: freshwater enters the creek through the spillway and creek banks while incoming tidal water from the adjacent lagoon enters at the mouth of Greens Creek. The only outflow source is also through the mouth of Greens Creek. The following equation describes the relationship between the prism and the flow and determines the HTT of a system:

$$HTT\ (time) = \Omega\ (m^3) / Q\ (m^3\ time^{-1}) \qquad \text{(eqn. 6)}$$

where Q is the total flow over a flood cycle and Ω is the basin prism.

In order to measure the water velocity, or total flow (Q), current measurements over a 30 hour cycle were taken using an Acoustic Doppler Current Profiler (ADCP) at the mouth of Greens Creek. The ADCP accounts for the detection of any velocity differences throughout the water column possibly due to stratification and tidal current processes. Flow (Q) (eqn. 7) during inlet recharge is determined by the relationship between velocity at the inlet (V) over the flooding cycle and the cross sectional area of the inlet (A) (Nichols and Biggs, 1985):

$$Q\ (m^3\ time^{-1}) = V\ (m\ time^{-1}) * A\ (m^2) \qquad \text{(eqn. 7)}$$

Velocity measurements over the depth of the water column were averaged to obtain an accurate flow measurement for water entering Greens Creek. The cross sectional area of the inlet was calculated by determining the average water depth and total width at the inlet of Greens Creek. By calculating the cross sectional area at both low and high water information was obtained for the determination of the tidal prism within Greens Creek.

The basin prism (Ω) or capacity of the basin is defined by several factors: the hypsometry of the basin, the boundaries of the basin, and the elevation of the outflow (Kjerve and Magill, 1989). The capacity of the basin was determined by measuring two key factors: bathymetric profiles of the basin and the elevation of the tide. The basin capacity (eqn. 8) was calculated from the following equation:

$$\Omega(m^3) = CSA(m^2) * L\ (m) \qquad \text{(eqn. 8)}$$

where CSA is the average cross sectional area obtained from the transects and L is the length of the creek obtained from a large-scale NOAA chart.

The estuary number (e) describes the potential flow characteristics of streamlines associated with conduits and is controlled by three processes: density gradients, turbulent mixing, and tidal mixing. Estuary number (eqn. 9) describes the nature of water as it passes through an orifice (i.e. inlet) and is calculated from the following:

$$\text{Estuary Number (e)} = [\Omega * (u_t)^2] / (g * h * Qf * Tt) \qquad \text{(eqn. 9)}$$

where Ω = tidal prism (volume)

u_t = time and depth averaged velocity of the tidal flow during the ebb duration

g = gravity constant (9.8 m s^{-2})

h = depth of the water column (m)

Qf = freshwater discharge

Tt = tidal period

Based on the velocity measurements obtained at the mouth of Greens Creek, the tidal prism (m^3) component of the equation was determined from the difference in basin capacity at slack low and slack high tide. In order to determine the freshwater discharge (Qf) (eqn. 10) from the stream at the head of Greens Creek, the cross sectional area of the spillway was calculated. In addition, current measurements with a small hand held current meter were determined at the spillway during the ebbing tide since this is the primary source of freshwater to the system. Discharge from the reservoir spillway was then calculated from the following equation:

$$Qf = Vs\ (m\ time^{-1})^* As\ (m^2) \qquad \text{(eqn.10)}$$

where Vs is equal to the time averaged flow through the spillway and As is the cross sectional area of the spillway. The area of the spillway (eqn. 11) was calculated simply by

$$As = \pi r^2 / 2 \qquad \text{(eqn. 11)}$$

since the spillway entrance is a concrete pipe where r is equal to the radius of the pipe. A calculated estuary number greater than 0.3 ($e > 0.3$) characterizes a fully developed turbulent jet in which the time averaged velocity of the tidal flow during the ebb duration term (u_t) dominates creating a well-mixed jet. However, a calculated estuary number less than 0.03 ($e < 0.03$) describes more stratified flow conditions typical of a plume.

Jet theory deals primarily with the duration and length of the ebbing flow but water depth also plays a very important role in determining the characteristics of the streamlines. The ratio of the lagoon depth (h_b) to the inlet hydraulic radius or simply the average inlet depth (h_o) in addition to the slope of the shoreface determines the allowable expansion of the turbulent flow streamlines. The presence or absence of streamline expansion characterizes whether a jet is deemed axial or planar. In general, if the ho:hb ratio is greater than 1 then the streamlines are able to spread (characteristic of a planar jet). Depending on the slope of the bottom the streamlines may still always be in contact with the bottom thereby restricting expansion. Typically, shoreface slopes greater than

0.11 degrees do not have an influence on streamline expansion in instances when $h_o:h_b >$ 1. However, when ho:hb is less than 1 there is no allowable expansion of the turbulent flow streamlines characteristic of an axial jet.

In order to determine the parameters of the streamlines an echosounder was used to determine the appropriate h_b and h_o depths. From the two obtained depth measurements, the shoreface slope of the bottom was determined by simple geometry. The ratio of these depths in addition to the shoreface slope determines the axial or planar nature of the streamlines.

The determination of the above tidal parameters will provide valuable insight into the behavior of upland nutrients entering into Greens Creek system and explain how tidal exchange affects that behavior.

CHAPTER II
BACKGROUND OF THE RESEARCH

Precipitation

Importance of Rainfall

Research on the importance of atmospheric deposition to ecosystems has long been an area of concern for many oceanographers, yet very few reports were published until the late 1960's and early 1970's. Although today there is a new interest in precipitation chemistry there is still much uncertainty with regard to the role of rainfall as a source of nutrients to an ecosystem. It is the present belief that a significant fraction of nutrients, total nitrogen in particular, are entering coastal and marine ecosystems through atmospheric depositions. However, the exact role of these inputs in relation to the health of these ecosystems is still undetermined (Hinga et al., 1991; Fisher & Oppenheimer; 1991; Jickells, 1995; Valigura et al., 1996). Ecologically, the most productive areas of the world's waters are often nitrogen limited (Dugdale, 1967; Ryther & Dunstan, 1971; D'Elia et al., 1986); therefore, these N-limited environments are strongly influenced by anthropogenic depositions such as precipitation (Paerl, 1997). In numerous estuarine, coastal, and oceanic regions of the world, atmospheric N may provide a significant source available for new phytoplankton production.

Few studies have addressed the question of rainfall nutrient bioavailability with regard to marine phytoplankton (Timberley et al., 1985; Peierls and Paerl, 1997). The Eastern Shore of Virginia has no sizable river systems; therefore, rainfall and groundwater are the dominant freshwater sources for this ecosystem. In particular, seaside coastal creek primary production such as that occurring in Greens Creek relies on both rainfall and groundwater as the primary means of nutrients entering the system. Also due to the lack of topographic changes on the Eastern Shore landscape the importance of rainfall related runoff is somewhat limited except in rare situations meaning nutrient loadings from rainfall are viewed as direct additions to the water column. The impacts and significance of groundwater nutrient inputs will be discussed in

detail in the following chapter. The main goal of this section of the research is not only to define the quantity of atmospheric deposition but to also investigate the availability of rainfall as a nutrient source for coastal phytoplankton. Recent studies have shown the importance of atmospheric N in supporting algal productivity and growth on short (1-2 day) time scales (Peierls and Paerl, 1997).

The primary N species of interest are nitrate and ammonium with DON concentrations becoming more of a recent concern. Studies have concluded that DIN (NO_3 + NH_4) contribute 25-35% of the total nutrient input due to rainfall (Tyler, 1988; Fisher & Oppenheimer, 1991; Hinga et al., 1991; Scudlark & Church, 1993) with NO_3 concentrations typically greater than NH_4. Little is known about dissolved organic N depositions but literature dated back to the late 1960's reveals that DON in rainfall can be 49-65% of the total N (Prospero et al., 1996). The significance of the DON fraction in rain is only recently becoming of global significance and interest. As a result of nutrient enrichment due to rainfall inputs there is generally an alteration in N:P ratios which may induce changes in phytoplankton community structure. Nitrogen and phosphorus species are most often the focus of atmospheric depositions even though there is no significant atmospheric source of P (Fisher & Oppenheimer, 1991). Phosphorus is still an important nutrient control and should not be overlooked since it plays a vital role in phytoplankton dynamics. It is also important to remember that constituent concentrations vary both in space and time due to event duration, rainfall volume, wind patterns, pollutant sources, seasons, and atmospheric chemistry. These spatial and temporal variations also bring about much concern. Although many questions have been answered by years of investigations, there is still much uncertainty when it comes to conclusions about precipitation chemistry and its impact on an ecosystem.

Historical Background

Valiela et al. (1978), pioneers of precipitation research in the marine environment, examined the significance of nutrient inputs to the Great Sippewissett Marsh (Falmouth, Massachusetts) from precipitation. They concluded that no seasonal pattern in nutrient concentrations could be detected but to some degree the variation was dependent upon

the amount of rainfall (Fig. 4). Figure 4 shows that as rainfall duration increases the concentrations of nutrients decreases thus concluding that the first few centimeters of a rainfall event sweep nutrients out of the atmosphere. The maximum nutrient concentrations decreased for single precipitation events as the rainfall persisted thus the initial precipitation removed the particulate matter to which the dissolved nutrients must be adsorbed. Results from this study also suggested that nitrate was the primary inorganic nitrogen species loaded to the marsh by precipitation followed by ammonium (Table 3). Significant amounts of dissolved organic nitrogen and phosphate were also measured in the samples, although the authors believe their calculated DON input is somewhat an underestimate due to improper sample storage. Similarly, Correll and Ford (1982) studied the effects of nitrogen loading by precipitation in the Rhode River, a subestuary of the Chesapeake Bay, and results concurred with those of Valiela et al.(1978) in which nitrate concentration in rainfall was the dominant nitrogen species followed by ammonium concentrations. They also concluded that nitrate concentrations have been steadily increasing for 7 years especially in summer due to increased fossil fuel combustion over this time period and may have implications on future eutrophication concerns.

TABLE 3. Annual inputs of nutrients into the Great Sippewissett Marsh by precipitation (Valiela et al., 1978).

Nutrient	kg year $^{-1}$
NO_3	52.0
NO_2	0.2
NH_4	31
Dissolved Organic N	89.2
Particulate N	6.5
Total N	178.9
PO_4	23.8

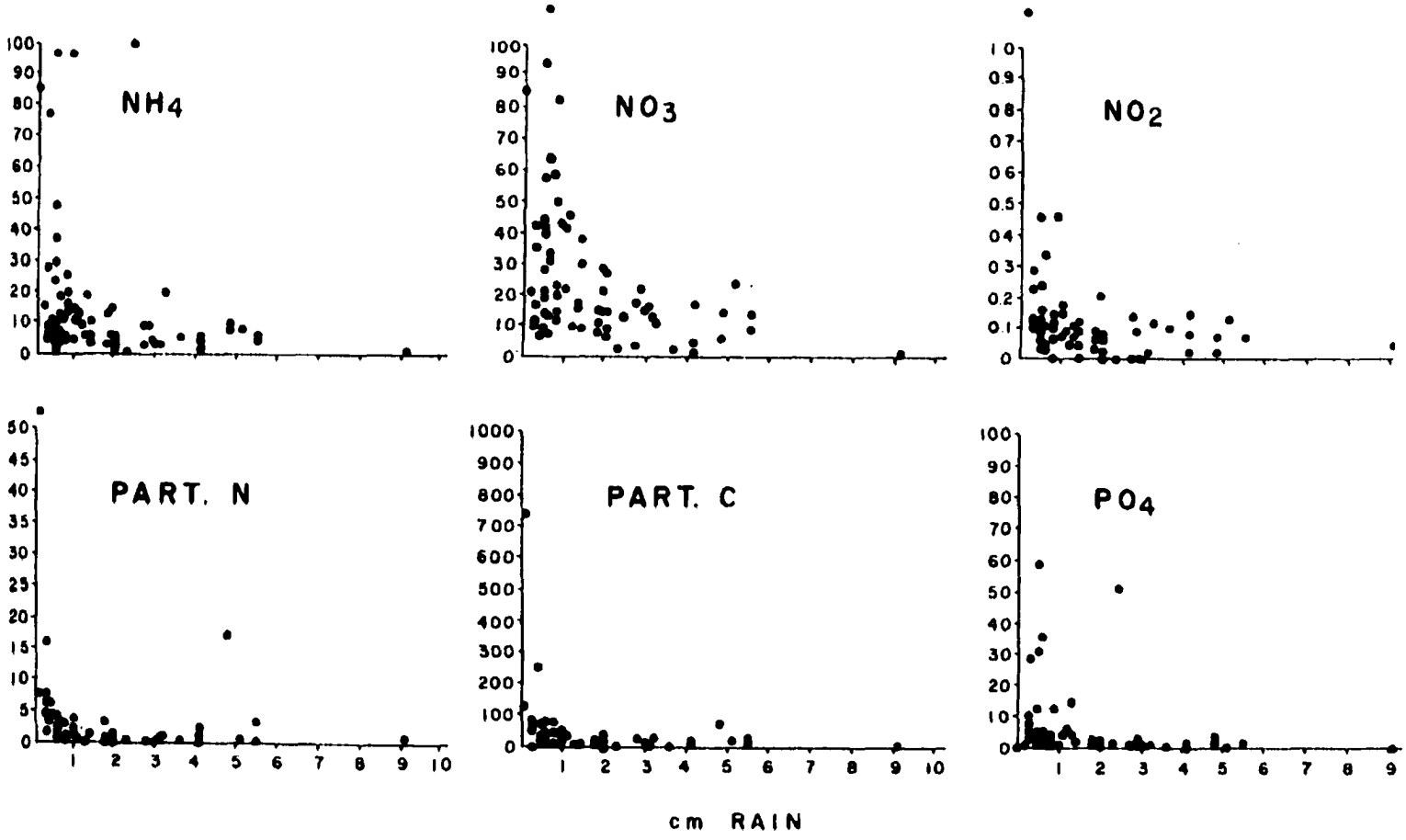

Fig. 4. Nutrients in precipitation, measured in μg-atoms per liter, in relation to the amount of precipitation (Valiela et al., 1978).

Although researchers such as Valiela et al. (1978) and Correll & Ford (1982) opened the doorway to the importance of rainfall as a nutrient source to ecosystems it was not until the late 1980's that other researchers began to focus on its significance. The findings published in a report by Fisher et al. (1988a) suddenly stimulated global interest in atmospheric depositions and the impact on coastal eutrophication. Findings (Table 4) suggest that in addition to the more commonly considered agricultural and sewage nutrient loadings, nitrogen deposited from the atmosphere is a major fraction of the total anthropogenic nitrogen loadings to the Chesapeake Bay.

TABLE 4. Calculated nitrogen loadings to Chesapeake Bay Watershed (Fisher & Oppenheimer, 1991) including the relative percentage of the total sources and also as a percentage of non-point sources (NPS).

Source	10^4 kg N yr^{-1}	kg N ha^{-1} yr^{-1}	% of total	% of NPS
Precipitation				
nitrate	151	9.2	24	26
ammonium	84	5.1	13	14
Animal Waste	195	11.9	31	33
Fertilizer	158	9.6	25	27
NPS Subtotal	588	35.9	----	100
Point Sources	41	2.5	7	----
Total	*628*	*38.3*	*100*	----

Table 4 concludes that atmospherically derived dissolved inorganic nitrogen (NH_4 + NO_3) contributes ~37% of the total loading of this primary nutrient and is approximately equal to that from fertilizers and animal waste products. Published findings of Fisher et al. (1988a) and Fisher & Oppenheimer (1991) have forced serious re-investigations with the primary purpose of determining the significance of atmospheric inputs to ecosystems.

The role of atmospherically derived dissolved inorganic nitrogen (wet + dry) was also investigated for the Delaware Bay (Scudlark & Church; 1993) in relation to other large-scale continental inputs such as municipal/industry, rivers, salt marshes and benthic fluxes from sediments. Their specific goals were to 1.) measure both direct (deposition to surface waters) and indirect (watershed runoff) atmospheric DIN ($NH_4 + NO_3$) source inputs to the Delaware Bay, 2.) to assess the spatial and temporal variability associated with atmospheric fluxes, and 3.) to compare atmospheric inputs to other large-scale DIN sources. As seen in Figure 5, the total atmospheric deposition (wet plus dry) and municipal/ industrial activities accounted for ~14% and ~41% of the total annual DIN inputs to the Delaware Bay estuary, respectively (Scudlark and Church, 1993). Of that total atmospheric deposition, a large fraction is deposited indirectly from watershed runoff with the remainder being directly deposited into the bay waters.

During the summer months when the combined river inputs are typically at a minimum, atmospheric inputs are greatest and account for ~25% of the total DIN input into the estuary (Fig. 5). Inputs due to municipal/industry during the summer months only increase slightly but are still the dominant DIN source for the system. The atmospheric influence during the summer months is of ecological significance in that it provides an external N source to sustain water-column productivity during those months of maximum N limitation.

Precipitation Variability

The variability in atmospheric deposition has many sources: the duration and volume of the rainfall event (Valiela et al., 1978), seasonality (Sisterson et al., 1989; Scudlark & Church, 1993), the storm tract in relation to pollutant sources (Fowler & Cape, 1984), and atmospheric mixing. The significance of the numerous sources of variability when researching atmospheric deposition is that the differences among rainfall events can obscure the determination of long-term trends. Jordon et al. (1995) analyzed long-term trends in precipitation chemistry in order to determine the extent of interannual variability of rainfall constituents. The study was conducted at the Rhode River on the western shore of the Chesapeake Bay and sampling occurred on an event basis.

Assessing the magnitude of temporal variability requires a long-term monitoring program. This is a central problem in precipitation chemistry research in that most conclusions have been inferred from limited data. To overcome this problem, the conclusions by Jordon et al. (1995) are based on a long-term watershed and estuary monitoring program beginning in 1973.

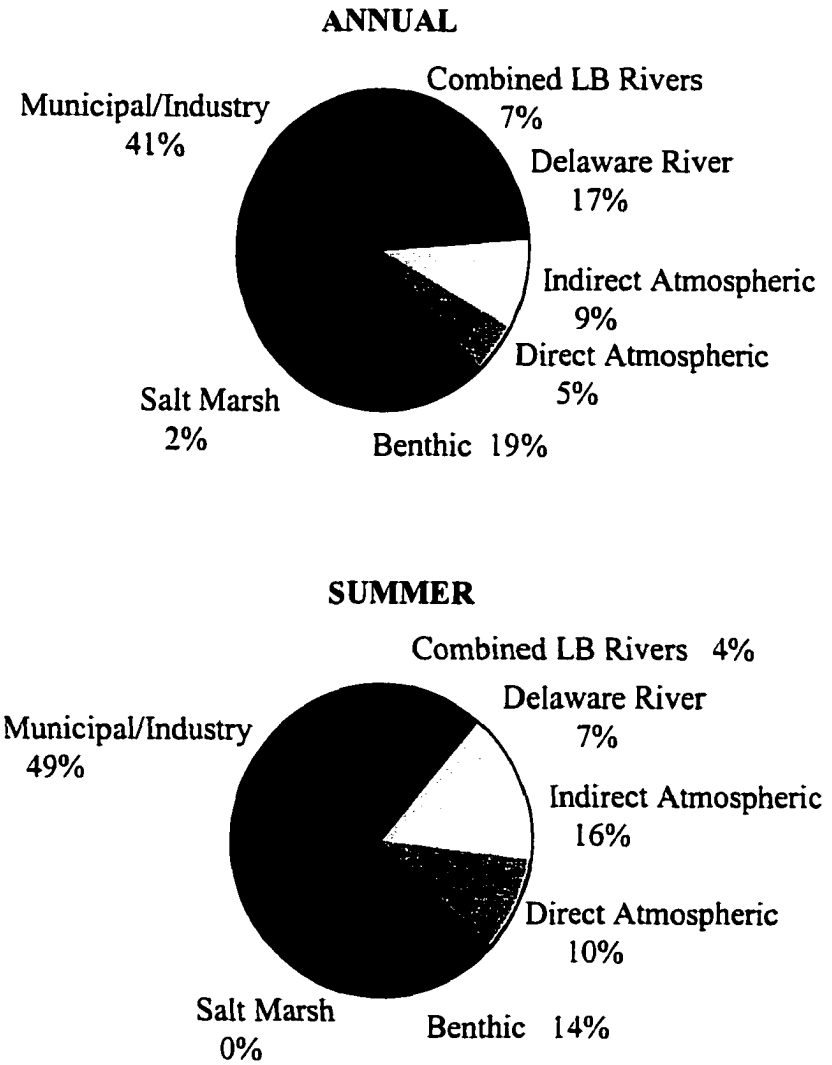

Fig. 5. Relative (top) annual and (bottom) summer DIN (NO_3 + NH_4) fluxes to the Delaware Estuary (Scudlark & Church, 1993).

The focus of this research was to examine the temporal variability of rainfall constituents at different time scales. The results of testing the long-term trends in monthly mean concentrations weighted by the volume of rainfall in each event. The yearly data (1973-1991) shows that in bulk precipitation (wet plus dry deposition) H_3O^+, NH_4^+, Ca^{2+}, and NO_3^- concentrations all increased over the sampling period while TON, TOP, and TOC concentrations decreased. Overall, no constituent showed significant trends between bulk and wet depositions yet concentrations differed greatly among rainfall events, precipitation volume within events, and time lag between events.

TABLE 5. Comparison of atmospheric and riverine inputs to the global oceans (all as 10^9 moles per year) (all data from Duce et al., 1991).

Element	Riverine [a]	Atmospheric [b]
N (excluding N_2 gas)	1500-3570	2140
Cd	0.0027	0.0036-0.0063
Cu	0.16	0.03-0.11
Ni	0.19	0.24-0.29
Fe	19.7	519
Pb	0.01	0.43
Zn	0.09	0.17-0.92

[a] Dissolved input, particulate components are assumed to be deposited in coastal areas.

[b] Total (dissolved + particulate) input.

In addition to field sampling, Jordon et al. (1995) used a regression model to predict constituent concentrations for each month, precipitation volume, and the time since the last event to evaluate how each affected interannual variability. The results of the event model suggest that concentrations of many constituents in rainfall vary seasonally due to changes in wind patterns, pollutant sources, timing and volume of precipitation events, and atmospheric chemistry. The most significant conclusion of this

study was the long-term increase in nitrate concentrations in bulk precipitation throughout the sampling period (1973-1991). This is a similar finding of Correll & Ford (1982) that nitrate concentrations have been steadily increasing for 7 years (1973-1980) especially in summer due to increased fossil fuel combustion over this time. This increasing nitrate loading may have serious implications on future eutrophication and acidification concerns of ecosystems.

On a more global scale, Jickells (1995) reviewed the magnitude and effects of atmospheric metal and nutrient inputs to the oceans. Although a main problem when attempting to understand long-term trends is a lack of time series data, the evidence is still clear that flux estimates from the atmosphere are a major route by which metals and nutrients reach the ocean (Table 5). It is also clear that there is great diversity of the chemical constituents that contribute to these fluxes (Table 6).

TABLE 6. Species composition of atmospheric N inputs to the North Sea (all data from Rendell et al., 1993).

Component	Mode of Deposition	Flux 10^9 moles yr^{-1}
NO_3^-	Dry	4.3
NH_4^+	Dry	2.0
HNO_3	Dry	1.6
NH_3	Dry	1.5
NO_3^-	Wet	13.1
NH_4^+	Wet	7.2
DON	Wet	1.7
Total atmospheric input		31.4
Riverine input		71.4

The next question to be addressed is the regional significance of these atmospheric depositions. In addition to the importance of atmospheric N deposition and the associated temporal variability in small and large-scale ecosystems, spatial variations must also be considered. Now large spatial variations must be considered. Regional waters such as the Western Baltic Sea, the Western Mediterranean Sea, Atlantic Ocean coastal waters, and the stratified waters of the North Pacific Ocean receive anywhere from 10-70% of their total new N input from atmospherically derived N (Table 7). On average 20-40% of the total new N inputs for the world's receiving waters are of an atmospheric origin with most of them attributable to increasing agricultural, urban, and industrial emissions (Paerl, 1997). With regard to the eastern seaboard of the United States the North, Mid- and the South Atlantic regions receive atmospherically derived N contributions of approximately 23%, 50%, and 27% of new N inputs respectively. Due to the eastward advection of U.S. urban and agricultural nitrogen emissions (Galloway et al., 1984), the Mid-Atlantic waters receive the largest input of atmospherically derived N over other eastern coastline regions (Scudlark & Church, 1993).

TABLE 7. Estimated contributions of atmospherically derived N to the total new N inputs in diverse, estuarine, coastal, and open-ocean waters (Paerl, 1997).

Receiving Waters	New N as AD-N sources and forms*	References
Baltic Sea (proper)	>25% W+D, I	Rodhe et al. 1980; Elmgren 1989; Ambio 1990
Western Baltic Sea (Kiel Bight)	60% W+D, I	Prado-Fiedler 1990
North Sea (coastal)	20-40% W+D, I	GESAMP 1989
Western Mediterranean Sea	10-60% W, I	Martin et al. 1989; Loye-Pilot et al. 1990
North Pacific Ocean		
Stratified surface waters	40-70% W+D, I	Prospero & Savoie 1989
Water Column	<5%	Prospero & Savoie 1989

TABLE 7 Continued.

Receiving Waters	New N as AD-N sources and forms*	References
Sargasso Sea		
Surface waters	~25% W, I	Duce 1986
Water column	~10% W, I	Michaels et al. 1993
Waquiot Bay, Massachusetts	29% W, I+O	Valiela et al. 1997
Narragansett Bay	12% W, I+O	Nixon 1995
Long Island Sound	20% W, I+O	Long Island Sound Study 1996[a]
New York Bight	38% W, I+O	Valigura et al. 1996
Chesapeake Bay	27% W, I	Chesapeake Bay Prog. 1996[b]
Rhode River, Maryland	40% W, I+O	Correll and Ford 1982
Neuse River-Pamlico Sound,		
North Carolina	38% W+D, I	Paerl and Fogel 1994
Atlantic Ocean coastal waters,		
North Carolina	35-60% W+D, I	Paerl and Fogel 1994
Sarasota Bay, Florida	26% W+D, I	Sarasota Bay NEP 1996[c]
Tampa Bay, Florida	28% W+D, I	Tampa Bay NEP 1996[c]

* Wet deposition – W; dry deposition – D; inorganic – I; organic – O.

[a] Supported by U.S. EPA/NOAA

[b] Supported by U.S. EPA/NOAA, Maryland, District of Columbia, Pennsylvania, Chesapeake Bay Commission

[c] Sarasota & Tampa Bay National Estuarine Programs supported by NOAA, EPA, FL.

With the Mid-Atlantic regions of the U.S. receiving approximately 50% of the total atmospherically derived nitrogen it is important to consider the dramatic variations in both N species and concentrations that can occur in this region due to weather conditions. Researchers have concluded that atmospheric N concentrations have

increased within the past decade; thereby, increasing the threat of coastal eutrophication. Sources of atmospheric N - whether natural or anthropogenic- along with atmospheric circulation patterns determine the species composition of rainfall. Species composition and concentrations may have potentially large gradients from urban to remote regions of the mid-eastern states making it important to conduct precipitation research in various locations.

Impact on Greens Creek

Research has in the past focused primarily on urban regions and large watershed areas such as the Chesapeake and Delaware bays. However, due to the large temporal and spatial variations associated with precipitation chemistry the effects must be observed in a variety of ecosystems. It is often difficult to assess the effects of rainfall N and P inputs in areas affected by multiple nutrient input sources such as industry/municipal, agriculture, and forests. There have been few studies addressing the bioavailability of atmospheric N and P in supporting algal productivity and growth on the Eastern Shore. Since the Eastern Shore of Virginia has no sizable freshwater river systems, this peninsula receives freshwater only from small groundwater driven creeks such as Greens Creek and precipitation. These characteristics make it an ideal environment to study the impacts of direct rainfall N and P loading in a primarily agricultural ecosystem and the importance of these additional nutrients on coastal productivity.

Groundwater

Importance of Groundwater

The balance (or lack there of) between incoming nutrient sources and phytoplankton uptake within an estuary is still not well understood. Generally, estuarine research has only considered freshwater as an endmember within large estuaries without understanding the precise sources and impacts of those nutrient rich freshwater. It has only recently been noted that groundwater flow comprises one of the major pathways by which freshwater is transported to the sea (Bokuniewicz, 1980; Johannes, 1980; Weiskel

and Howes, 1991; Millham and Howes, 1994). It is also commonly viewed as a mechanism by which nutrients, sediments or other chemicals flux directly from the terrestrial to the marine environment (Harvey and Odum, 1990; Oberdorfer et al., 1990; Valiela et al., 1990). Groundwater inputs to the nearshore marine environment are an important biogeochemical and environmental factor in many coastal regions of the world. In a region not dominated by large river systems, such as the Eastern Shore, groundwater represents the hydrologic link between terrestrial and marine ecosystems; thus, the examination of groundwater nutrient fluxes will allow us to better understand the impact that upland activities have on these systems. The primary focus of this section of research is to not only quantitatively illustrate the importance of groundwater as a nutrient source but to also understand the impact of this source on coastal production. In addition to increasing our knowledge of groundwater fluxes, another focus is to improve our knowledge of groundwater assessment methods (Millham and Howes, 1994; Loaiciga and Buddemeier, 1996). It is often difficult to discern the impacts of industry, agriculture, municipalities, and forests on groundwater quality. The Eastern Shore, Greens Creek in particular, provides an opportunity to observe the effects of a wholly agricultural environment on groundwater nutrient concentrations. Today, nutrient management programs are being devised to reduce non-point source nutrient loadings that are believed to contribute to the degradation of surface water quality in many coastal embayments.

North Atlantic Perspective

In 1996, Nixon et al. focused on understanding the biogeochemical exchanges within the complex environment between free-flowing freshwater and the edge of the continental shelf, including intertidal wetlands, estuaries, and the shelf. The focus was to assess the magnitude of the biogeochemical influences bordering the land-sea margin of the North Atlantic so that an estimate of the net transport of N and P from land onto the continental shelf (100-200 meter water depth). In order to develop a annual mass balance of N and P on the continental shelf of the North Atlantic Ocean, Nixon et al. (1996) provide estimates of the net N and P flux from the land to the continental shelf (Table 8).

Nixon et al. (1996) investigated the water flow from five major rivers which discharge directly onto the continental shelf on the western side of the North Atlantic and concluded the effective flux was estimated to be $292*10^9$ moles y^{-1} of N and $13*10^9$ moles y^{-1} of P. In addition, the riverine fluxes that are not direct additions to the continental shelf must pass through estuaries and their associated wetlands before reaching the shelf where they undergo intense biogeochemical reactions. It is estimated that estuarine processes retain and remove 30-65% of the total N and 10-55% of the total P, which would otherwise be available to the coastal ocean through variations in water residence times. Table 8 shows that N and P inputs by large rivers are a primary nutrient source for the continental shelf and can account for 42% and 47.2% of the total N and P loaded onto the shelf (Nixon et al., 1996).

TABLE 8. A preliminary assessment of active N and P inputs to the continental shelf (0-200m) of the North Atlantic Ocean. These estimates do not include an additional $122*10^9$ moles y^{-1} and $40*10^9$ moles y^{-1} of P that are carried by five large rivers and buried with riverine sediments in deltas and on the continental shelf. Units are 10^9 moles yr^{-1}.

	N	P
Inputs		
Direct atmospheric deposition	133	Very small
Biological nitrogen fixation	~20	0
Estuaries	172-335	11-19
Very large rivers	292	13
Total	627-780	24-32

Regional Focus

Large estuaries such as the Delaware Bay (Sharp et al., 1982), San Francisco Bay (Peterson et al., 1985) and Chesapeake Bay (Reay et al., 1992) which are dominated by

intense industrial, municipal and agricultural activities are typically of major concern to coastal oceanographers. These large estuaries have rivers associated with them supplying tremendous quantities of freshwater to the estuarine system. River flow is generally the primary control of estuarine nutrient variability on both seasonal and interannual time scales; therefore, upstream river characteristics have important consequences on downstream estuarine variability (Peterson et al., 1985). For example, Sharp et al. (1982) state that the Delaware River, the main river source to the Delaware Bay as well as the site of many major industrial and municipal activities, has a mean yearly flow of 332 m^3s^{-1} with an annual variability ranging from 80 to 2,800 m^3s^{-1}. The Delaware Bay is the second largest port in tonnage in the United States and its 33,000 km^2 drainage basin serves about 5% of the population of the country (Sharp et al., 1982). Results show that there are very high nutrient inputs (nitrate concentrations near 200μM) that occur at the freshwater end with the abundant nutrients gradually being used by phytoplankton throughout the estuary due to light attenuation of the turbid waters. In terms of productivity of the Delaware estuary, it has been speculated that the high suspended sediment load brought into the estuary by the Delaware River causes the system to be severely light and not nutrient limited thus allowing only moderate productivity to occur throughout the estuary.

In coastal embayments not dominated by large rivers, small freshwater creeks, such as Greens Creek, are influenced by groundwater discharge (Valiela et al., 1978; Giblin and Gaines, 1990; Millham and Howes, 1994; Staver and Brinsfield, 1996) and rainfall (Valiela et al., 1978; Ogden and Julien,1993; Hussein et al.,1994; Montgomery and Dietrich,1995) as the primary means by which nutrients are loaded into the system. Giblin and Gaines (1990) examined the importance of nitrogen inputs from groundwater and road runoff in a small coastal marine cove (Town Cove) on Cape Cod, Massachusetts. Town Cove has an average depth of 2.2 meters with a maximum depth of 6m and an area of 1.4×10^6 m^2 with a volume of 3.13×10^6 m^3. They assessed groundwater inputs by three different methods: a water budget (assuming discharge equals recharge), direct measurements of discharge using bell jars and a salt and water budget at the mouth of the cove over several tidal cycles. Overall, the budget of salt and water yielded the best results and showed that the rate of N-loading to Town Cove from

groundwater exceeded the nitrogen loading from sewage discharge reported for many large river dominated estuaries (Table 9). The total nitrogen inputs from freshwater sources (groundwater and runoff) to Town Cove totaled 361 mmol m^{-3} $year^{-1}$. Giblin and Gaines (1990) conclude that nitrate inputs due to groundwater which is often overlooked represents a significant source of nitrogen enrichment to many coastal embayments.

TABLE 9. A comparison of the nitrogen input from freshwater sources to a variety of estuaries (Giblin and Gaines; 1990). All data compiled by Nixon & Pilson (1983).

		Freshwater Nitrogen Inputs (mmol N m^{-3} $year^{-1}$)
	Volume of Freshwater (* 10^9 m^3 per yr)	Land
Chesapeake	74,000	50
Narragansett	2,200	60
Delaware	1,330	70
Potomac	7,150	80
Pamlico	980	250
South San Francisco		160
North San Francisco		<5
Raritan		50
New York		800

Significant efforts have been made to investigate surface water quality in the Chesapeake Bay but only recently has the focus turned to groundwater discharge and its impact on surface water quality (Reay et al., 1992). It has been well documented that groundwater nutrient concentrations are indeed coupled to the dedicated use of the overlying land (Valiela et al., 1978; Johannes, 1980; Hallberg, 1986; Giblin and Gaines, 1990; Valiela et al., 1990; Correll et al., 1992; Reay et al., 1992; Valiela, 1992; Millham

and Howes, 1994; Staver and Brinsfield, 1996). For example, agriculture is deemed to be the primary land use throughout much of the Chesapeake Bay watershed, including the Eastern Shore, which suggests that the groundwater flow associated with these land practices has contributed to the elevated nitrate levels within the bay (Reay et al., 1992; Staver and Brinsfield, 1996). Reay et al. (1992) conducted a study to evaluate nitrogen concentrations in surface water, groundwater and groundwater discharge in Cherrystone Inlet, on Virginia's Eastern Shore. They combined seepage meter deployments and synoptic surface water sampling to demonstrate the impact of nitrate in groundwater discharging from agricultural land on the water-column nitrogen availability in the southern Chesapeake Bay. Results concluded that shallow groundwater underlying agricultural fields had nitrate concentrations significantly higher (up to 20 times greater) than inlet surface waters or groundwater underlying forested lands (Table 10) and that this groundwater did indeed discharge at rates of 0.02 to 3.69 liters m^{-2} hr^{-1} to adjacent surface waters.

TABLE 10. Upland Groundwater and Watershed Creek Dissolved Inorganic Nitrogen and Phosphorus Concentrations. Standard error of the mean and sample size is denoted within parentheses. (Data from Reay et al., 1992)

Site	Adjacent Land Use	NO_3^- $\mu mol\ L^{-1}$	NH_4^+ $\mu mol\ L^{-1}$
Eyreville	Agricultural	652.2 (32.2,52)	2.5 (0.2,51)
Eyrehall	Agricultural	602.7 (32.5,13)	2.8 (0.5,14)
Steelman	Agricultural	222.0 (19.2,10)	9.0 (0.5,8)
Old Castle	Forested	6.6 (2.0,16)	12.9 (3.3,18)
Scott	Forested	81.8 (28.3,7)	5.5 (1.3,5)

TABLE 10 Continued.

Adjacent Site	NO_3^- Land Use	NH_4^+ $\mu mol\ L^{-1}$	$\mu mol\ L^{-1}$
Watershed Stream			
Headwaters (N=5)	Mixed	135.0 (31.0,15)	23.9 (6.8,15)

Discharge rates were also found to be greatest during periods of low tide and decreased with increasing distance offshore. Groundwater discharge adjacent to agricultural lands was characterized primarily by nitrate (~99% of the dissolved inorganic nitrogen) shifting to ammonium farther offshore. Reay et al. (1992) conclude that nitrogen contributions from direct groundwater discharge and tidal creek inputs appear to be of significant ecological importance and therefore must be considered in future water quality assessments. Other recent groundwater nitrate studies (Capone and Bautista, 1985; Giblin and Gaines, 1990) have also reported nitrate groundwater concentrations to be well below those determined for groundwater underlying agricultural fields (Reay et al., 1992; Staver and Brinsfield, 1996).

Agricultural practices are often singled out as the primary contributor of nutrients, specifically nitrogenous compounds, to nearshore environments (Sewell, 1982; Correll et al., 1992; Reay et al., 1992; Staver and Brinsfield, 1996) due to the movement of groundwater beneath fertilized fields. Researchers are only beginning to realize the importance of this nutrient-rich freshwater flow as an important link to understanding the phytoplankton production that occurs within these estuarine-coastal environments. Research on wetland eutrophication typically shows that sudden algal blooms are often linked with the input of a particular missing nutrient, generally either nitrogen or phosphorus (Sewell, 1982). Hydrologically linked ecosystems interact through the flow of waterborne nutrients and sediments and thus these nutrients discharged from many upland ecosystems pass through the lowlands of fresh or brackish wetlands on their way

to estuaries and the sea (Correll et al., 1992). Watersheds represent natural, easily definable ecosystems which allows one to evaluate land-water interactions in the context of various land management practices, yet agricultural ecosystems are complicated by the complexity and variability of these management practices (Lowrance et al., 1985). Agricultural watersheds have a variety of nutrient sources, including precipitation, fertilizers, atmospheric fixation, irrigation, weathering of soils and groundwater which is often neglected since it does not directly affect daily agricultural management practices (Lowrance et al., 1985; Correll et al., 1992; Reay et al., 1992; Staver and Brinsfield, 1996).

Impact on Greens Creek

Small freshwater creeks influenced by groundwater, such as Greens Creek, may input equivalent concentrations of nutrients as large rivers on a per volume basis. These freshwater creeks associated with many of the estuaries along the North Atlantic coastline are often neglected as nutrient sources for the open ocean as compared to their large river counterparts. It is important to emphasize that only recently has there been a growing appreciation for the impact that these small coastal environments may have on coastal and possibly even open ocean primary production. Knowledge of their role in transporting nutrients from the terrestrial to the marine environment is still far from satisfying.

Water Quality

Factors Controlling Water Quality

Researchers have long been trying to determine the factors that regulate phytoplankton growth and production within aquatic ecosystems. The large differences in the rates and patterns of nutrient assimilation and cycling among estuaries have been well documented. However, there is still much uncertainty regarding the sources of variability that can limit phytoplankton production. Since the early 1970's, coastal

researchers have increasingly been investigating the response of phytoplankton growth to both nutrient enrichment and limitation in estuaries. Typically, the focus of phytoplankton growth limitation studies has been on the relative importance of N, P, and other trace elements such as iron, but more recently light availability has received increasing attention within estuarine ecosystems.

Over the years, there have been debates regarding the roles of N and P in regulating phytoplankton biomass in estuaries, coastal areas and fjords (Jordan et al., 1991; Fisher et al., 1992; Comin and Valiela, 1993; Fong et al., 1993) which seasonally have varying mixtures of fresh and seawater. Classic phytoplankton research has generally proposed that fixed nitrogen in coastal waters occurs in low concentrations relative to the nutrient requirements of marine plants (Ryther and Dunstan, 1971; Eppley et al., 1979; Johannes, 1980). Yet, recent research has concluded that nitrogen contributions from direct groundwater discharge and precipitation appear to be of significant ecological importance to the coastal marine system and are readily converted to phytoplankton biomass. Thus, those processes controlling the delivery of nutrients entering the marine environment may also govern primary production in these nearshore coastal environments (Jordan et al., 1991). In order to obtain a more complete understanding of phytoplankton uptake within an estuary it is critical to evaluate the relevance of the advective freshwater movement from the groundwater driven creeks to the enrichment of the surrounding algal community (Jordan et al., 1991).

Over time, significant changes may occur in the phytoplankton dynamics of an ecosystem: 1) increased nutrient inputs may promote increases in phytoplankton biomass, 2) shifts in phytoplankton community structure, and 3) changes in phytoplankton speciation may occur (Harding, 1994). Two main ecological consequences of these changes are an increased amount of particulate organic matter (POM) derived from an increased abundance of phytoplankton biomass and reduced water clarity caused by the increased biomass (Harding, 1994). Overall, the spatial differences in light versus nutrient limitations on phytoplankton rely on the variations in incident light, particulate matter inputs, vertical mixing, river discharge rates, external nutrient sources, and nutrient uptake rates along the salinity gradient.

The Role of Light vs. Nutrient Limitation in the Chesapeake Bay

Temporal and spatial variations related to alterations between light- and nutrient-limitations on phytoplankton growth are of extreme importance to the health of Chesapeake Bay and its surrounding tributaries (Pennock & Sharp, 1994). Light (the energy source to drive photosynthesis) availability is regulated primarily by incident light, suspended particulate matter, and the depth of the surface mixed layer while nutrient availability is determined by freshwater inputs (rivers, rainfall, and groundwater) and in situ biogeochemical processes (Pennock & Sharp, 1994). An important feature of the Chesapeake Bay is the location of the turbidity maximum along the salinity gradient which results from the flocculation of freshwater-derived material and the two-layered circulation typical of estuaries which promote particulate retention (Fisher et al., 1988). Stratification in these systems is generally controlled by salinity and temperature with a well defined surface mixed layer (Fisher et al., 1988).

Fisher et al. (1988) addressed the problem of phytoplankton abundance in the Chesapeake Bay by focusing on the variability in horizontal and vertical gradients of turbidity, nutrients, and phytoplankton. The large spatial and temporal variations in freshwater flow into the bay with regard to both particulate and nutrient loadings have an extensive impact on the interaction between light and nutrient limitations on algal abundance (Fisher et al., 1988; Pennock & Sharp, 1994; Harding, 1994). Evidence suggests that phytoplankton growth is suppressed in the zone of the turbidity maxima characterized by turbid, nutrient-rich waters while further downstream optical depths increase allowing phytoplankton biomass to increase with associated nutrient concentration decreases. This suggests that phytoplankton in the upper reaches of the bay tend to be light limited while a large portion of the Chesapeake Bay population downstream of the turbidity maxima tends to experience nutrient limitation (Fisher et al., 1988).

In estuaries such as the Chesapeake Bay and, speculatively, also small coastal creeks such as Greens Creek that have seasonally varying mixtures of fresh and salt water, there is evidence for seasonal and spatial shifts in the limiting nutrient (Fisher et al, 1992) for phytoplankton growth. Nutrient enrichment bioassays were used to examine

nutrient limitation of phytoplankton growth rates in which incubations persisted for 24 hours at 60% of ambient sunlight in an on-deck incubator. Water samples were obtained along the main stem of the Chesapeake Bay with subsamples for nutrient analysis. Changes in growth rates were estimated by changes in chlorophyll-a concentrations that were measured fluorometrically. Due to the freshwater inflow, the spatial distribution of surface salinity along the main stem of the Chesapeake Bay showed a steady increase in salinity with increased distance from the head of the Bay as expected. Fisher et al. (1992) show evidence that after the winter/spring maximum in freshwater flow (1) the DIN:PO4 was greater than the N:P of the algal biomass; (2) phosphate turnover times were short; (3) ammonium turnover times were long and (4) phytoplankton were stimulated by additions of phosphate and not by additions of ammonium or silicate (Table 11). Evidence also showed that during the summer, or periods of limited discharge, all indicators reversed and nitrogen limited algal growth rates (Table 11).

TABLE 11. Summary of nutrient addition bioassays conducted along the main stem of the Chesapeake Bay of 1987. Stations are identified as distance from the Susquehanna River mouth (km). In May bioassay results at the 6 km station showed no response, and no bioassays were performed at km 177 or 214 (Fisher et al., 1992).

Station (km)	May		August	
	Salinity	*Bioassay*	*Salinity*	*Bioassay*
6	0.24	No response	4.38	-
74	7.91	Exclusive P	12.22	Primary N
119	10.32	Exclusive P	13.90	Primary N
177	11.77	-	15.80	Primary N
214	12.67	-	19.93	Exclusive N
283	15.39	Primary P	25.12	Exclusive N

TABLE 11 Continued.

NOTE: 'Exclusive' N or P limitation of phytoplankton growth rates are defined as having occurred when the addition of the exclusive limiting nutrient (either N or P) had the same effect as the addition of both N and P. "Primary' N or P limitation of growth rates is defined as a significant response to the addition of a primary nutrient (either N or P) with the largest response due to the addition of both nutrients.

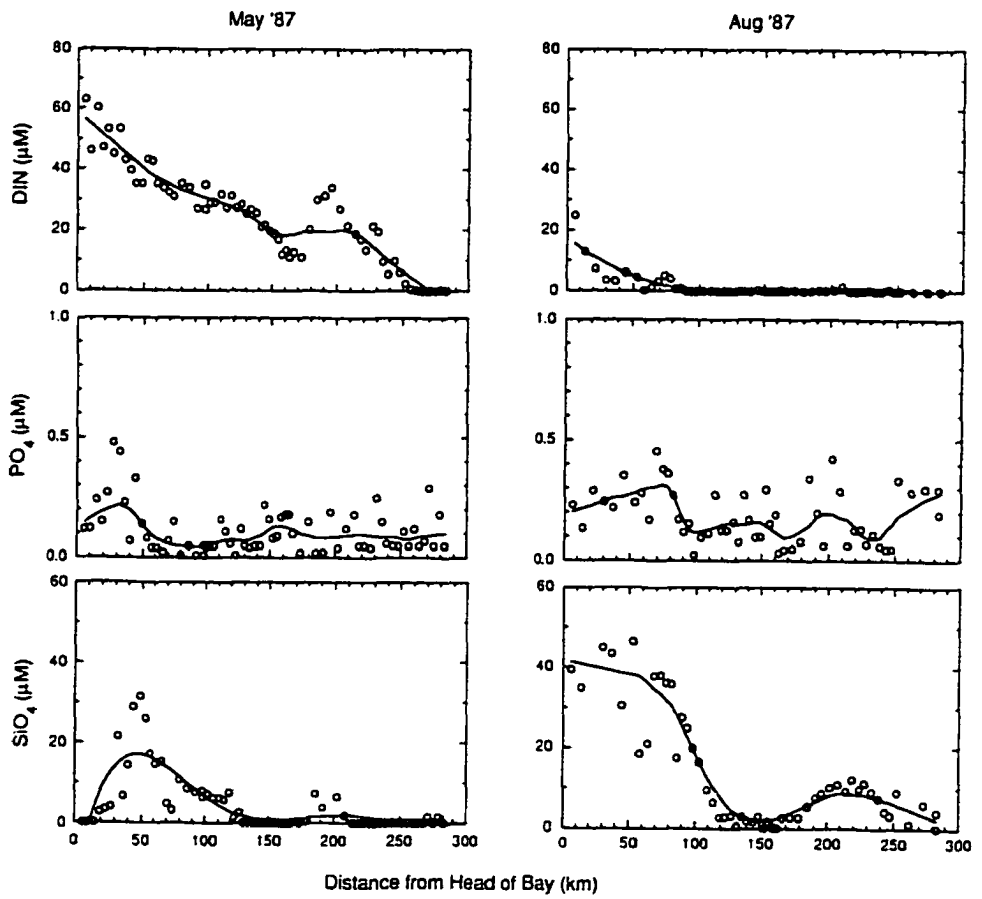

Fig. 6. Spatial distribution of DIN (DIN = nitrate + nitrite + ammonium), soluble reactive phosphate (PO_4), and reactive silicate (SiO_2) in surface waters of the Chesapeake Bay in May and August 1987. Lines were polynomial equations fitted to the data to average spatial variability (Fisher et al., 1992).

With regard to the seasonality of nutrient limitation, Fisher et al. (1992) conclude that P and Si limit phytoplankton growth in the spring when freshwater river discharge is greatest and N concentrations are high (Fig. 6). However, during summer months when river discharge is low into the Chesapeake Bay and salinity is high, nitrogen limits algal growth (Table 12). It is evident that seasonal changes shift the balance from P to N limitation from spring to summer and is based primarily on seasonal variations of river discharge. These results coincide with the results of D'Elia et al. (1986) for the Patuxent subestuary, Fong et al. (1993) for experimental microcosms in the Pacific Estuarine Research Laboratory, an outdoor facility adjacent to the Tijuana estuary, and Comin and Valiela (1993) for the Encanyissada and Tancada lagoon in Spain.

TABLE 12. Conceptual model for the seasonal basis of nutrient limitation of algal biomass in the Chesapeake Bay (Fisher et al., 1992).

	Spring	Summer
Inputs:	River dominated discharge	Wastewater, seawater more Important [1]
	Lower salinities	Higher salinities [2]
	Excess N available	N and P inputs decreased [2]
		P increased relative to N due to Sewage [1]
Sediments:	Oxygenated	Anoxic [3]
	PO_4 sorption and storage	PO_4 release [3]
	Coupled nitrification and denitrification	Decoupled [4]
Algal biomass:	P-limited	N-limited [2]
	Diatoms dominate	Flagellates dominate [5]
	Si controls taxonomy	Si unimportant [6]
	Biomass maximum	Productivity maximum [7]
	Sedimentation high	Sedimentation low [7]

TABLE 12 Continued.

	Spring	Summer
	Organic decomposition creates summer anoxia	Biomass turns over rapidly in the water column [7]

Sources:
1 Fisher (1988)
2 Fisher et al. (1992)
3 Boyton and Kemp (1985)
4 Jenkins and Kemp (1984)
5 Sellner (1987)
6 Conley and Malone (1992)
7 Malone et al. (1986)

Chesapeake Bay: Long Term Trends

Harding (1994) reviewed over 40 years (1950-1990) of phytoplankton abundance data within the Chesapeake Bay to determine the long-term effects of light and nutrient limitations. Complicating seasonal variations in river discharge and the subsequent effects on light versus nutrient limitations are just a few of the effects of the long term changes in dissolved inorganic nutrient concentrations within the Chesapeake Bay (Harding, 1994). Harding's results concurred with those of Fisher et al. (1992) on the seasonality of P to N limitation within the bay but also showed that the nutrient concentrations and ratios have dramatically changed since the 1960's (Harding, 1994). Figure 7 depicts the six regions of the Chesapeake Bay evaluated by Harding (1994). His results suggest that dissolved inorganic nitrogen concentrations (DIN) have approximately doubled since the 1960's in the upper reaches (regions V-VI of Fig. 7) of the Chesapeake Bay (Fig. 8) despite N removal efforts, while orthophosphate concentrations have typically declined (Fig. 9) (Harding, 1994). Phosphate concentrations have been significantly reduced in the Bay as a result of point and

nonpoint source reductions most notably the ban of phosphates in detergents which occurred in the early 1980's. These changes in both DIN and PO_4^{3-} over the past 20-30 years have altered N:P nutrient ratios and have implications for nutrient limitations within the lower reaches (regions I-IV of Fig. 7) of the Chesapeake Bay.

Despite decades of field studies, factors controlling phytoplankton growth and production are not yet well defined in all aquatic systems leading to even more uncertainty about their rates of growth and productivity.

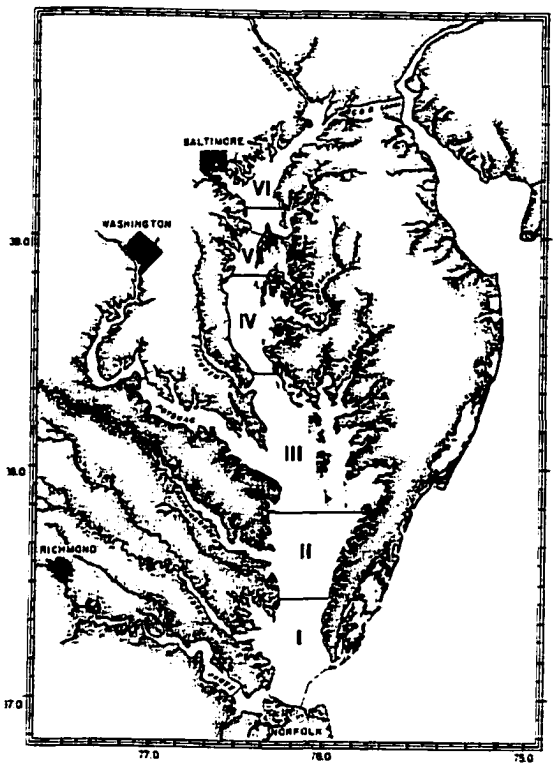

Fig. 7. Chesapeake Bay and surrounding tributaries and the six geographic regions (Harding, 1994).

Impact on Greens Creek

Now that the primary sources of nutrient loading have been discussed for Greens Creek, it is important to focus on the impacts that both groundwater and rainfall has on

the primary production within the system. Greens Creek is a coastal system associated with high suspended sediment concentrations that strongly attenuate light and possibly constrain phytoplankton growth. There is a continuous flux of freshwater discharge (i.e. groundwater) into the creek bringing with it nutrients (N, P, and Si) available for phytoplankton growth and suspended sediments with additional direct inputs by episodic rainfall events. Although phytoplankton growth in Greens Creek is strongly affected by the high turbidity, phytoplankton production is of great significance to the creek and adjacent lagoon. Estimates of primary production have been determined in similar systems with values ranging from 3.4 - 7.3 ng C ml^{-1} hr^{-1} (Blum, 1997). The estimates by Blum (1997) are suspected to be quite low since the experiments were conducted during high tides when a dilution factor becomes very important.

Nutrient and particle loading into Greens Creek is a local concern; thereby making monitoring programs with determinations for turbidity, nutrients, algal biomass and speciations, and light extremely important. Due to the lack of well documented research for this area of the Eastern Shore, there is much uncertainty about the rates at which nutrients and particulates are loaded into Greens Creek and the surrounding estuary. The first step to resource management is to understand those processes and factors that influence the health of Greens Creek so as to reduce some of the uncertainty regarding rates of inputs.

Eutrophication of Greens Creek and the adjacent Hog Island Bay is a major concern primarily of local fisheries and The Nature Conservancy - Virginia Coast Reserve especially with regard to nutrients (N and P) from adjacent fertilized agriculture fields and its impact on primary production. The chlorophyll produced by phytoplankton represents a food source for harvestable fisheries such as clams and oysters; thereby making it an important commodity within this system. Overall, understanding the levels of nutrient enrichment in Greens Creek will help determine the significance of terrestrial nutrient inputs into the adjacent lagoon and provide an important link to understanding the production occurring within this entire estuarine-coastal environment.

The results of this research will hopefully lead to a greater focus on sustainable environments by improving best management practices to reduce the need for fertilizers

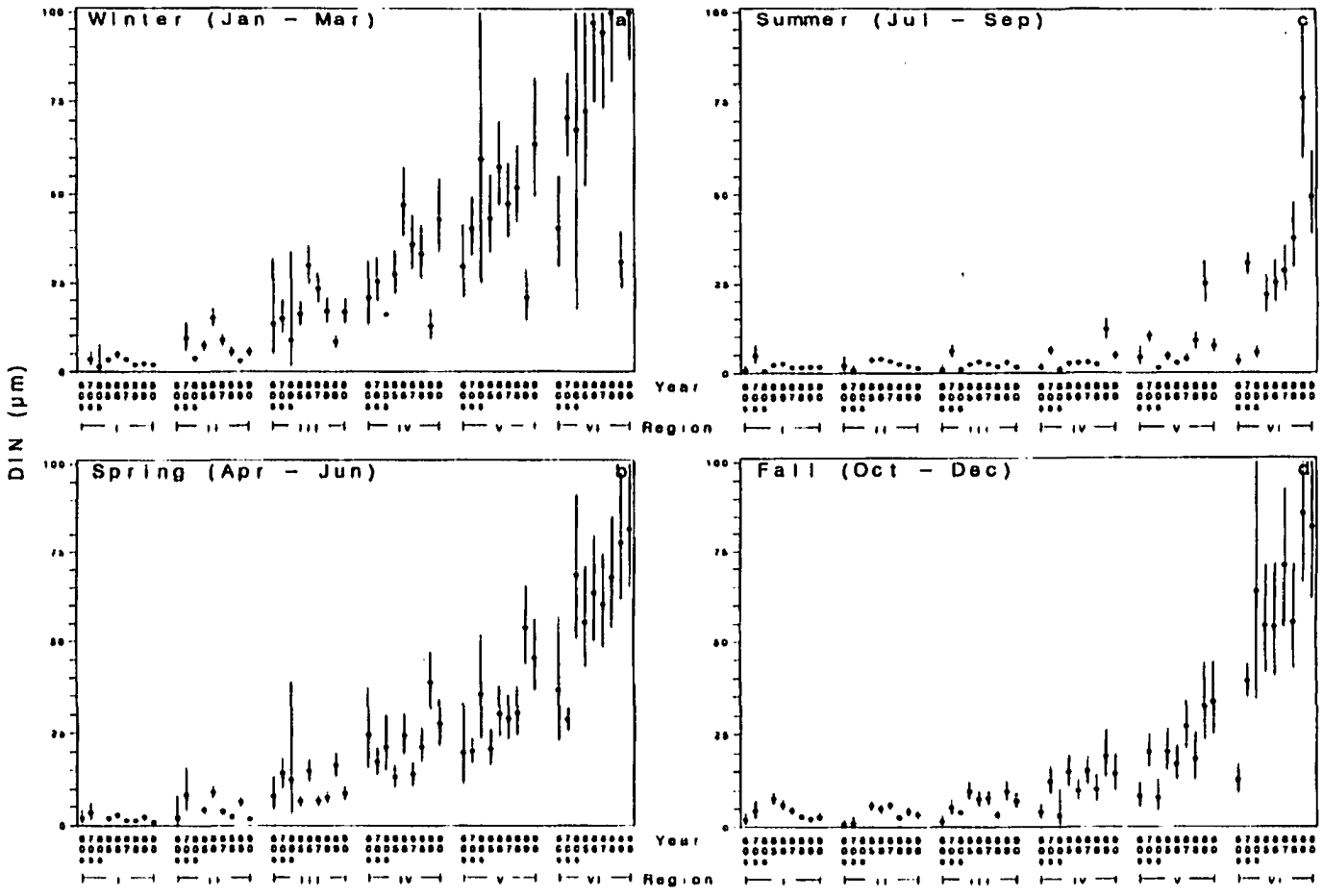

Fig. 8. DIN concentration by year, season, and region for 1960's, 1970's, and 1980's and individual years from 1985-1990. Error bars are 95% lower and upper confidence intervals (Harding, 1994).

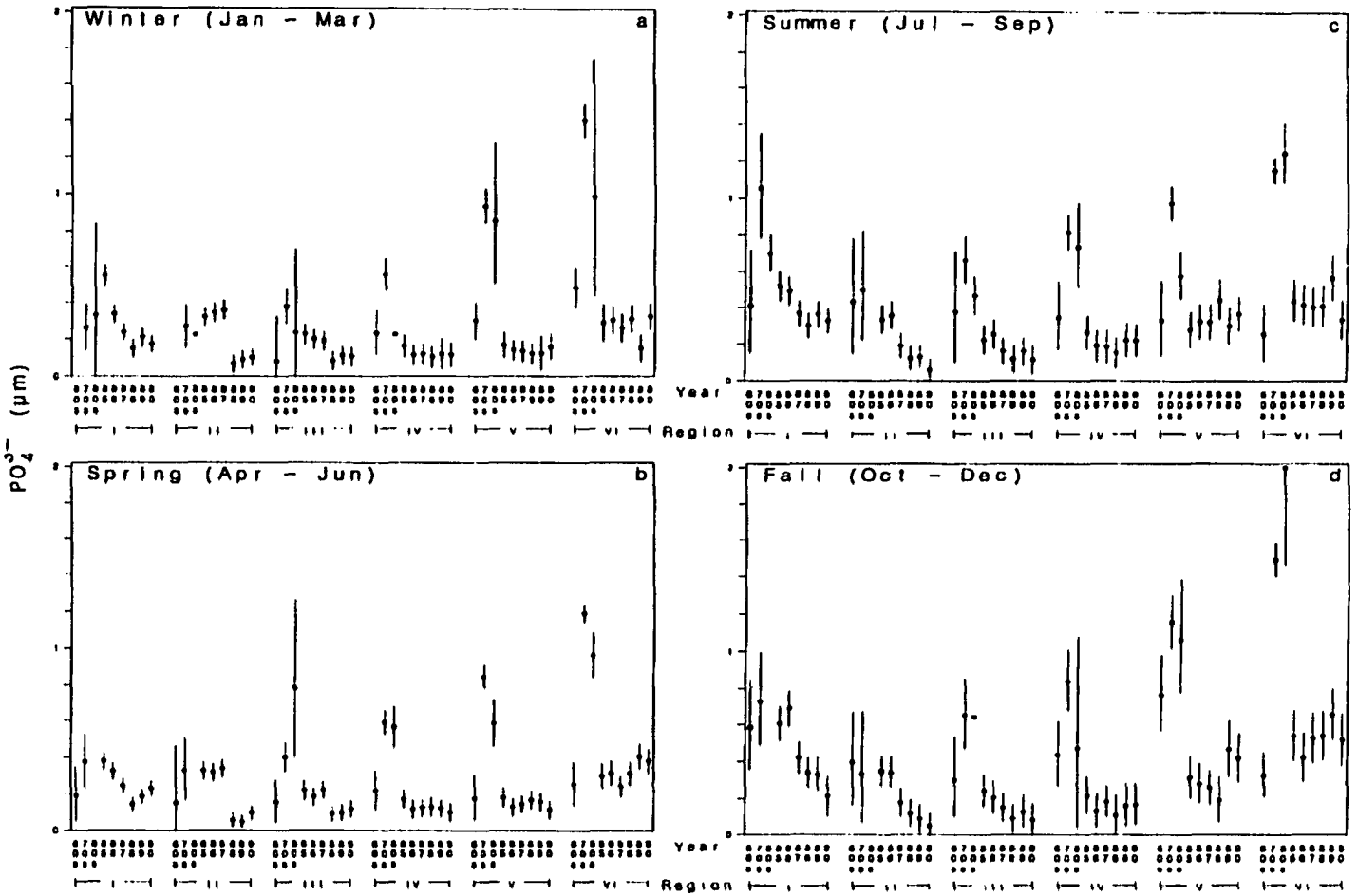

Fig. 9. Phosphate concentration by year, season, and region for 1960's, 1970's, and 1980's and individual years from 1985-1990 are shown. Error bars are 95% lower and upper confidence intervals (Harding, 1994).

and increasing attention to landscape ecology and habitat construction to create better buffer zones between land and water.

CHAPTER III
ANALYSIS OF THE DATA

Precipitation

The importance of atmospheric nutrients for marine primary productivity depends fundamentally on the biological availability of the nutrient species in rainfall events. The availability of atmospheric nutrients is controlled by many sources of variability including: duration of rainfall, volume of rainfall, seasonality, storm tracks in relation to pollutant sources and atmospheric mixing. Total rainfall volume was greater during sample year 1998 than 1997 with volumes measuring 49.47 and 33.76 inches respectively. The total rainfall volume for the first seven months of 1998 (Jan.-July) was equivalent to 33.67 inches while the total volume for the entire previous year (1997) was only slightly higher, 33.76 inches.

The total precipitation volume for all events occurring from October 1996 through July 1998 (n = 228) was equivalent to 85.15 inches, or an average volume of 3.87 inches per month; rainfall volume averaged 0.39 inches per event (+/- 1.77 inches) for all rainfall events. Over the study period (October 1996 through July 1998) there was no seasonal pattern in the rainfall volume (Fig. 10). The maximum measured rainfall volume was 3.91 inches on October 8, 1996 which marks the occurrence of tropical storm Josephine characterized by heavy rains and associated wind gusts up to 50 miles per hour. The average rainfall volume for the measured samples was determined to be 0.762 inches for the collected samples (n = 73) with volumes ranging from 0.05 – 3.91 inches. However, the overall rainfall volumes for all precipitation events per month throughout the study period are shown in Table 13 and varied greatly over the study period.

Figure 11 depicts the measured nutrient concentrations (μM) compared to actual rainfall volumes for each rainfall event. Generally, many researchers have concluded a trend in which nutrient concentrations are increased as precipitation volume per event decreases. Essentially, nutrients are believed to be swept out of the atmosphere with the first few centimeters of rainfall; therefore, as rainfall duration increases then nutrient concentrations tend to decrease. Although this nutrient data shows some seasonal

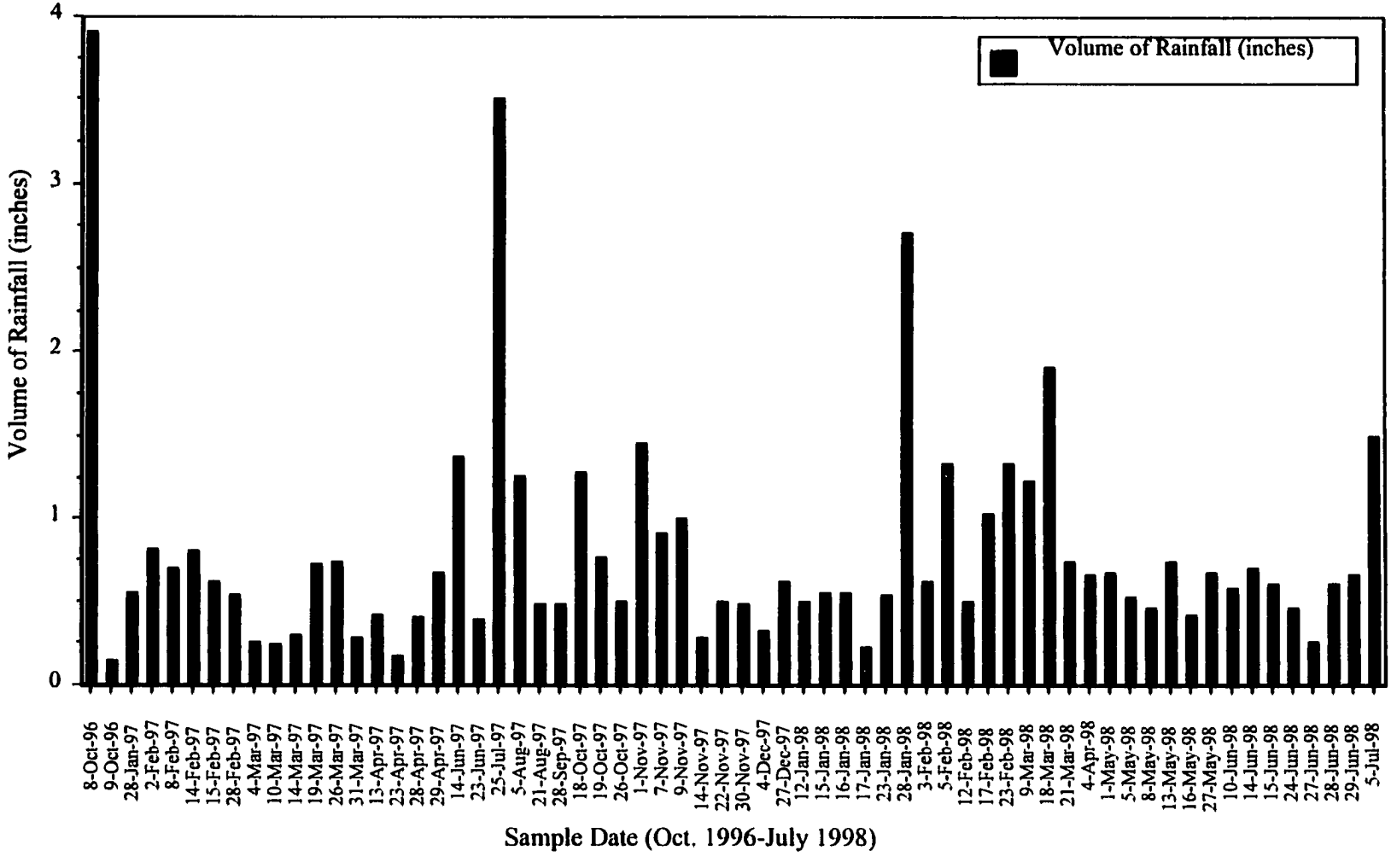

Fig. 10. Rainfall volumes, measured in inches, for collected nutrient samples (n = 73) over the duration of the sample period (October 1996 -- July 1998). Only rainfall events that yielded a minimum of 0.25 inches were collected.

TABLE 13. Total precipitation events throughout the study period (October 1996 – July 1998) with total number of events (n = 228) and average rainfall per volume event. Daily rainfall records courtesy of the Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, Virginia.

MONTH	SUM OF EVENTS (inches)	NO. OF STORMS	MEAN RAIN EVENT (inches)
Oct –96	6.02	7	0.86
Nov –96	3.22	9	0.36
Dec –96	5.25	17	0.31
Jan –97	2.22	7	0.32
Feb –97	3.83	8	0.48
Mar –97	3.23	11	0.29
Apr –97	2.96	12	0.25
May –97	1.80	10	0.18
Jun –97	1.83	5	0.37
Jul –97	5.02	8	0.63
Aug –97	1.96	5	0.39
Sep –97	1.19	8	0.15
Oct –97	3.83	12	0.32
Nov –97	6.10	13	0.47
Dec –97	3.02	13	0.23
Jan –98	6.83	12	0.57
Feb –98	7.20	10	0.72
Mar –98	5.04	12	0.42
Apr –98	2.18	14	0.16
May –98	5.27	15	0.35
Jun –98	4.61	12	0.38
Jul –98	2.54	8	0.32
TOTAL	**85.15**	**228**	**8.52**
MEAN	**3.87**	**10.36**	**0.39**
STD. DEV.	**1.77**	**3.17**	**0.18**

variations (Table 13), the concentration variations are to a large extent dependent upon rainfall volume. Maximum concentrations are centered on rainfall volumes of approximately 0.5 to 0.75 inches for all nutrient species (NH_4^+, NO_3^-, NO_2^-, and PO_4^{3-}) (Fig. 11). Therefore, these results also represent the general trend of decreased nutrient concentrations with increased rainfall duration. It is evident that nutrient concentrations varied greatly among rainfall events.

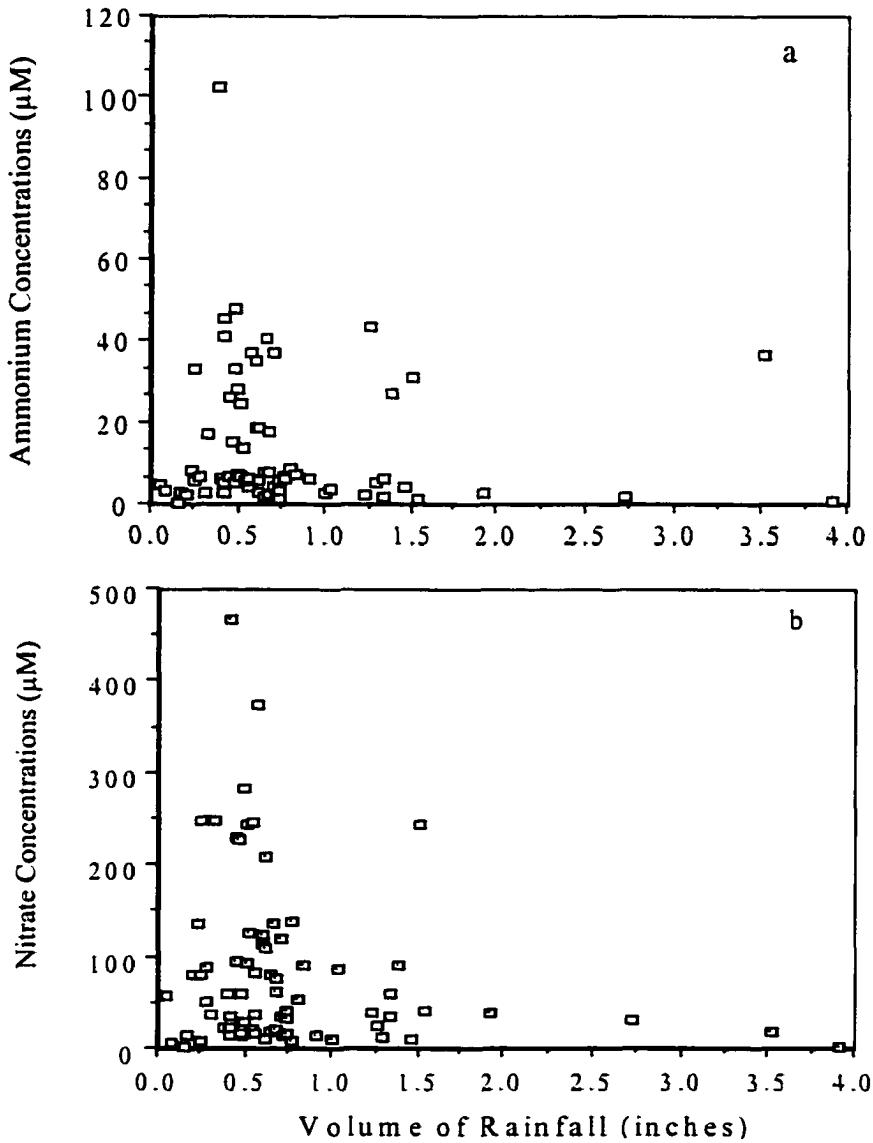

Fig. 11. Precipitation nutrient concentrations (µM): a.) ammonium, b.) nitrate, c.) nitrite and d.) phosphate verses volume of rainfall (inches) of all collected precipitation events (October 1996 – July 1998).

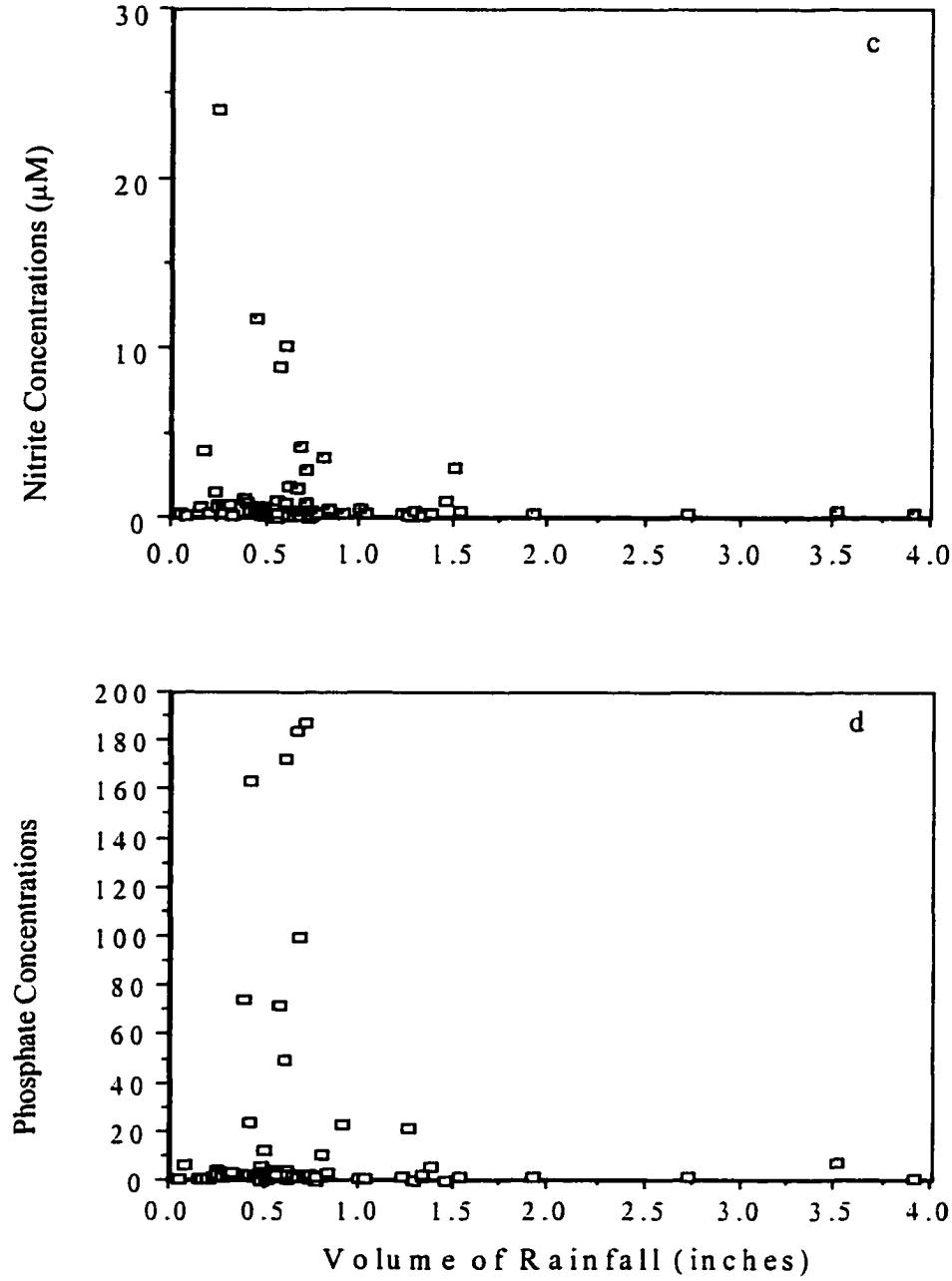

Fig. 11 Continued.

Concentrations of nutrient fractions were multiplied by rainfall volume to yield volume-weighted nutrient concentrations of precipitation events since nutrient concentrations are correlated with rainfall volume. The dominant DIN species observed were nitrate and ammonium with nitrite always of least significance. Throughout the

sampling period, nitrate was the predominant N species with concentrations consistently greater than ammonium concentrations except on June 23, June 25, August 5, and August 21, 1997 sampling dates (Fig. 12). The summer maximum was more evident for the 1997 sampling year than for 1998. However, it appears as if the ammonium peak was beginning just as the sampling was discontinued in the early summer of 1998. No seasonal trends were evident for nitrate concentrations, although there appears to be an increase in nitrate concentrations from sample year 1998 as compared to the previous year. Nitrite was the least abundant N-species measured during all sampling events with volume weighted NO_2^- concentrations showing large concentration variations similar to NO_3^- and NH_4^+. Nitrite concentrations ranged from 0.01 to 6.08 μM for all events with no discernible seasonal trends.

Phosphate concentrations also varied among precipitation events but a seasonal trend is more evident than for the previously described N species (Fig. 13). Phosphate concentrations measured from 0 to 427.80 μM over the sampling period with maximum concentrations consistently occurring during summer months (June – August) for both sample years despite the probable sample contamination. During the summer months of 1998, concentrations of PO_4^{3-} ranging from 68.88 to 427.80 μM were measured and are significantly higher than concentrations determined for previous sampling years. Although summer 1998 values are significantly higher than those measured in the previous summer, the elevated values are discarded although they do repeat the general trend of maximum values during the summer months. Elevated phosphate levels are suspected to have been contaminated during sample analysis due to increased phosphate levels in deionized water system.

Concentration totals, ranges, means and standard deviations are shown in Table 14 for all collected precipitation events. Overall, measured nutrient fractions showed large variations over the sampling period with NO_3^- concentrations representing the greatest total concentration of N as anticipated. However, NO_3^- also showed the greatest variation in concentrations compared to both NH_4^+ and NO_2^-. Total N concentrations were measured to be 3794.01, 737.15, and 54.541 μM for NO_3^-, NH_4^+, and NO_2^-, respectively.

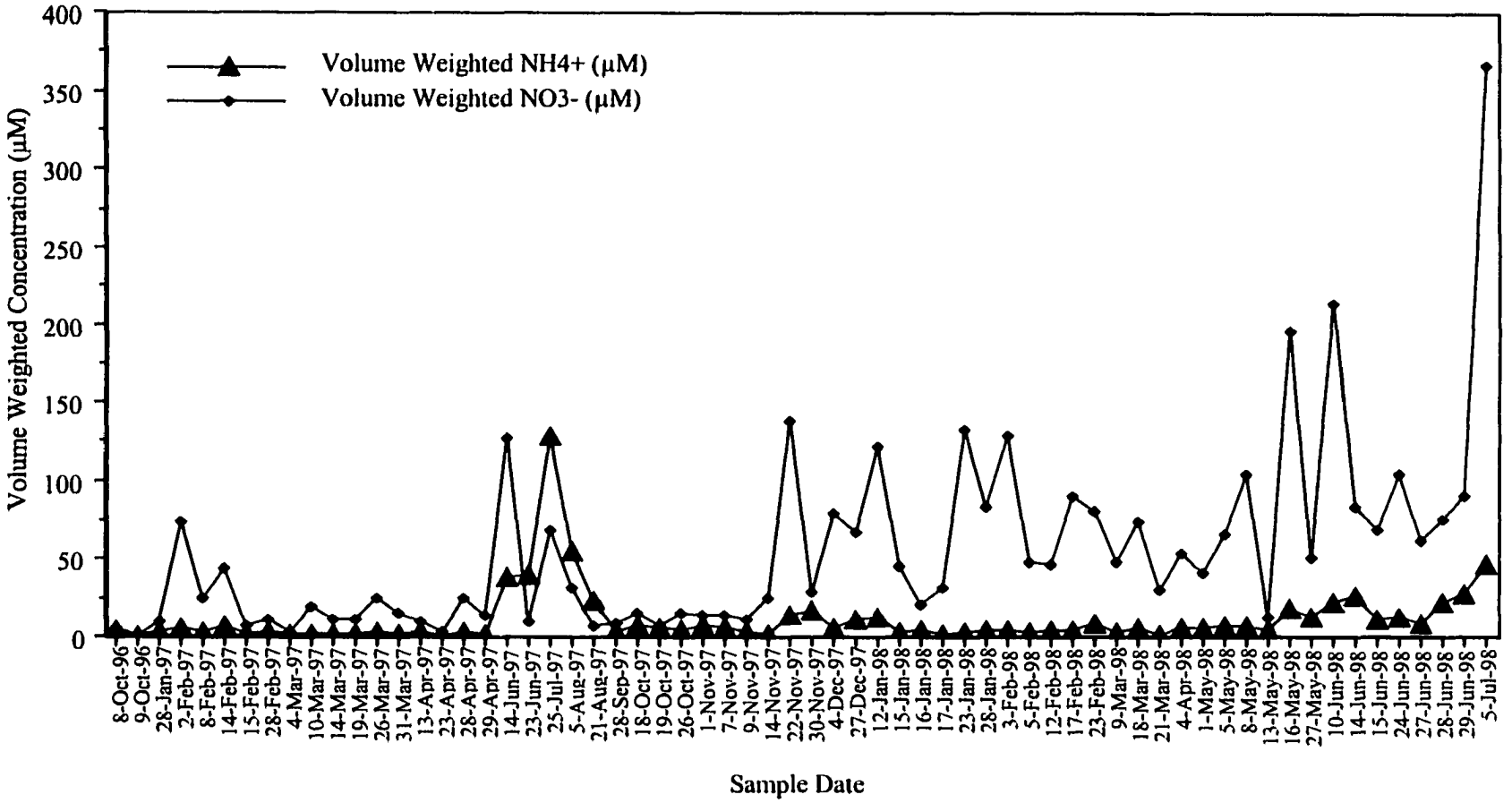

Fig. 12. Volume weighted concentrations (μM) of both nitrate and ammonium for all samples collected throughout the study period (October 1996 – July 1998).

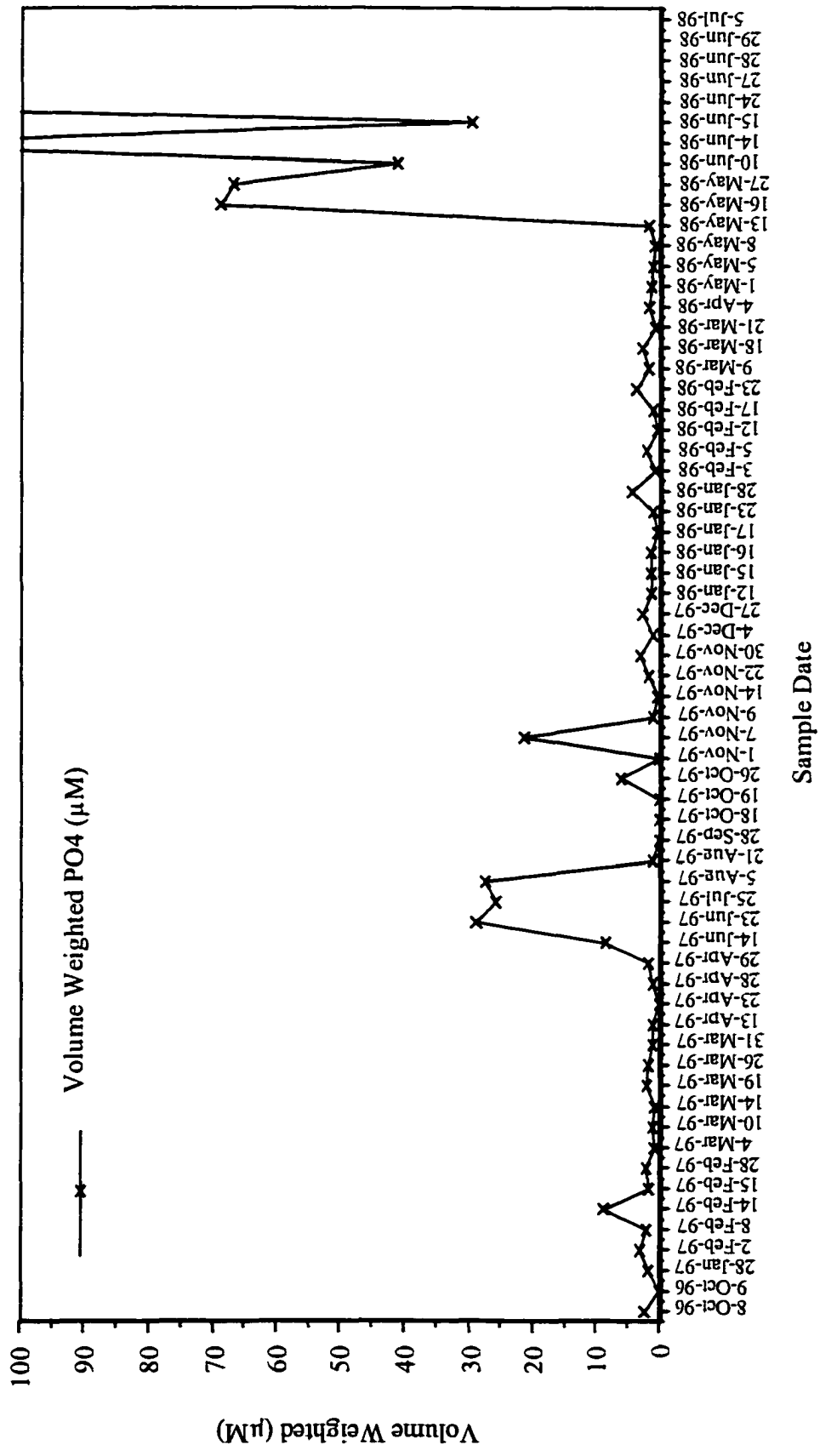

Fig. 13. Volume weighted concentrations (µM) of phosphate for all samples collected throughout the study period (October 1996 – July 1998). Maximum concentrations of 166.80 µM (24 June 1998) and 427.80 µM (5 July 1998) were omitted from the graph so that trends for concentrations less than 10 µM could be more easily visible.

Ammonium and nitrate concentrations were the most significant form of nitrogen with mean concentrations equivalent to 10.10 and 51.97 micromoles respectively. Nitrite concentrations were consistently the most negligible N species with volume weighted concentrations ranging from 0.01 to 6.08 μM for all collected events.

TABLE 14. Concentration totals, ranges (maximum and minimum measured values), means, and standard deviations of collected samples throughout the sample period (October 1996 – July 1998). All values are given in micromoles per liter. Sample size for NO_3^-, NH_4^+ and NO_2^- was n=73.

	NO_3^-	NH_4^+	NO_2^-	PO_4^{3-}
Concentration Total	3794.01	737.15	54.41	295.79
Maximum Concentration	366.37	128.87	6.08	74.17
Minimum Concentration	0.16	0.01	0.01	0.00
Mean	51.97	10.10	0.75	3.29
Standard Deviation	59.17	17.84	1.39	6.29

Although there is no significant source of atmospheric P, it is still considered in this research because it does have a significant role in marine primary productivity. Phosphate data from May 1998 to July 1998 was discarded from this analysis due to the high probability of sample contamination. Phosphate concentrations totaled 295.79 μM over the sample period with an average concentration of 3.29 μM per event and a large concentration range from 0 to 74.17 μM among individual samples.

In order determine the nutrient rainfall contribution available to phytoplankton in Greens Creek, event and yearly fluxes were calculated for all measured nutrient species with results shown in Table 15. Average loading rates were determined on a per event basis while yearly loading rates were determined based on an average of 124.8 storms per year. The average number of storms per year was derived from the daily rainfall records for data recorded during a two-year time span (1996-1998) at the ESAREC. These results

indicate that nitrate was the predominate DIN species loaded to the Greens Creek watershed with phosphate also being of significance. Loading rates equating to 3816.16 and 341.23 mg m^{-2} $year^{-1}$ for NO_3^- and PO_4^{3-} respectively were determined. Rainfall contributes a total of 5.52 ($*10^5$) moles DIN $year^{-1}$ and 2.89 ($*10^4$) moles P $year^{-1}$.

Percent compositions of the total atmospheric flux for each nutrient species were determined to be 4.83, 85.92, and 0.91 % for NH_4^+, NO_3^-, and NO_2^-, respectively. Overall, DIN species accounted for 91.66 % of the rainfall nutrient composition. Phosphate concentrations were estimated to be 8.32 % of the total rainfall composition with total DIN comprising the remainder. As expected, rainfall is composed primarily of N compared to P with NO_3^- accounting for approximately 86% of the available N in precipitation.

TABLE 15. Average event (mg m^{-2} $event^{-1}$) and yearly (mg m^{-2} $year^{-1}$) loading rates of N and P components of precipitation are presented. Percent compositions of the total atmospheric flux for each nutrient species are also given.

Loading Rate	NH_4^+	NO_3^-	NO_2^-	Total DIN	PO_4^{3-}
Average Flux	1.57	30.57	0.32	32.46	2.73
Yearly Flux	196.32	3816.16	40.49	4052.97	341.23
% Composition of the Total Flux					
	4.83	85.92	0.91	91.66	8.32

Rainfall Runoff Model

In addition to measuring the quantitative nutrient composition of rainfall events in the Greens Creek watershed, a rainfall related runoff model was also incorporated into this research. Rainfall related runoff, a significant component of nonpoint source

pollution, may contribute a significant amount of nutrients to the tidally influenced Greens Creek. The volume and composition of rainfall related runoff is primarily characterized by the land use types characteristic of the watershed. The runoff coefficient (RV), or the overall average ratio of runoff to rainfall, is highly correlated to the impervious surface area (IMP) of the watershed. The impervious surface area (IMP) is expressed as a percentage based on a given land use category for the watershed (Table 1). A runoff coefficient (eqn. 1) of 0.247 was determined for the Greens Creek watershed based on an IMP equal to 21% (a combination of a open space (0%) and a single family (42%) impervious service area) (Table 2). The total catchment area for Greens Creek watershed was calculated using a five-foot contour quadrangle map, with the total surface area equating to 8.14×10^6 square meters. For the purposes of this research, a correction factor (CF) was omitted from the calculations since it represents the spatial and temporal variations of rainfall between sites. This experiment was only calculated for a single watershed. Based on the results shown in Table 13, the average storm rainfall for the catchment was determined to be 0.39 inches, or 0.01 meters. Therefore, the average storm runoff volume (ASV) was determined to equal 2.01×10^{-4} m^3 for the Greens Creek watershed. Finally, the annual average storm runoff (AASV) for the Greens Creek watershed was calculated to be 2.50×10^6 m^3 $year^{-1}$ based on an average of 124.8 storms (NSTORM) per year. All parameters needed in this model were determined from the daily rainfall records maintained by the Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, Virginia.

This rainfall model serves as a predictive tool to determine nutrient runoff into Greens Creek based on the runoff coefficient (i.e. % groundcover), the mean rainfall volume and number of storms per year. For Greens Creek, the potential nutrient input per year from rainfall related runoff through the watershed is 2.42 ($*10^3$) mg DIN m^{-2} $year^{-1}$ (1.57×10^5 moles DIN $year^{-1}$) and 97 mg P m^{-2} $year^{-1}$ (8.23×10^3 moles P $year^{-1}$).

Groundwater Wells

Small freshwater creeks influenced by groundwater, such as Greens Creek, may input equivalent concentrations of nutrients as large rivers on a per volume basis and thus

be a significant factor in controlling primary production within estuarine systems. Sub-surface groundwater flowing perpendicular to the creek was measured with a series of shallow groundwater wells that follow a transect from the Greens Creek bank to the upland hammock area. The inorganic N species and phosphorus concentrations were measured as part of this shallow groundwater research. It is difficult to decipher any apparent seasonal trends in any individual DIN-species (NH_4^+, NO_3^- and NO_2^-) due to the differences between individual wells (beach, central and inland) and sampling dates (Fig. 14 a-c) throughout the study. Dissolved inorganic nitrogen inputs in the measured sub-surface shallow groundwater wells were primarily characterized by nitrate (49.9%) and ammonium concentrations (41.38%) with nitrite concentrations (8.7%) being of least significance. Ammonium concentrations (Fig. 14-a) ranged between 0.61 – 4.00 μM over the sampling period with higher concentrations measured in wells on April 1996, May 1996, and June 1997. Concentrations of NH_4^+ were generally highest in beach wells, closest to Greens Creek, as compared to both the inland and central shallow groundwater wells. In addition, inland wells typically had greater NH_4^+ concentrations than the central wells over the sampling period. Maximum ammonium concentrations occurred in the central well on May 1996 with measurements reaching 26.93 μM while minimum concentrations were determined to be 0.61 μM in the central groundwater well on January 1997.

Similar to the ammonium results shown in Fig. 14-a, there is no apparent seasonal trend in nitrate concentrations (Fig. 14-b) over the sampling period of this research. Concentrations of nitrate were generally greatest in the central groundwater wells as compared to both the inland and beach sub-surface shallow groundwater wells. Although, inland sub-surface shallow groundwater wells typically had lower nitrate concentrations than the beach wells over the sampling period. Nitrate concentrations (Fig. 14-b) typically ranged between 0 – 5 μM over the sampling period with higher concentrations (up to 70 μM) measured in sub-surface shallow groundwater wells from March to May 1998 as compared to all previous sampling dates.

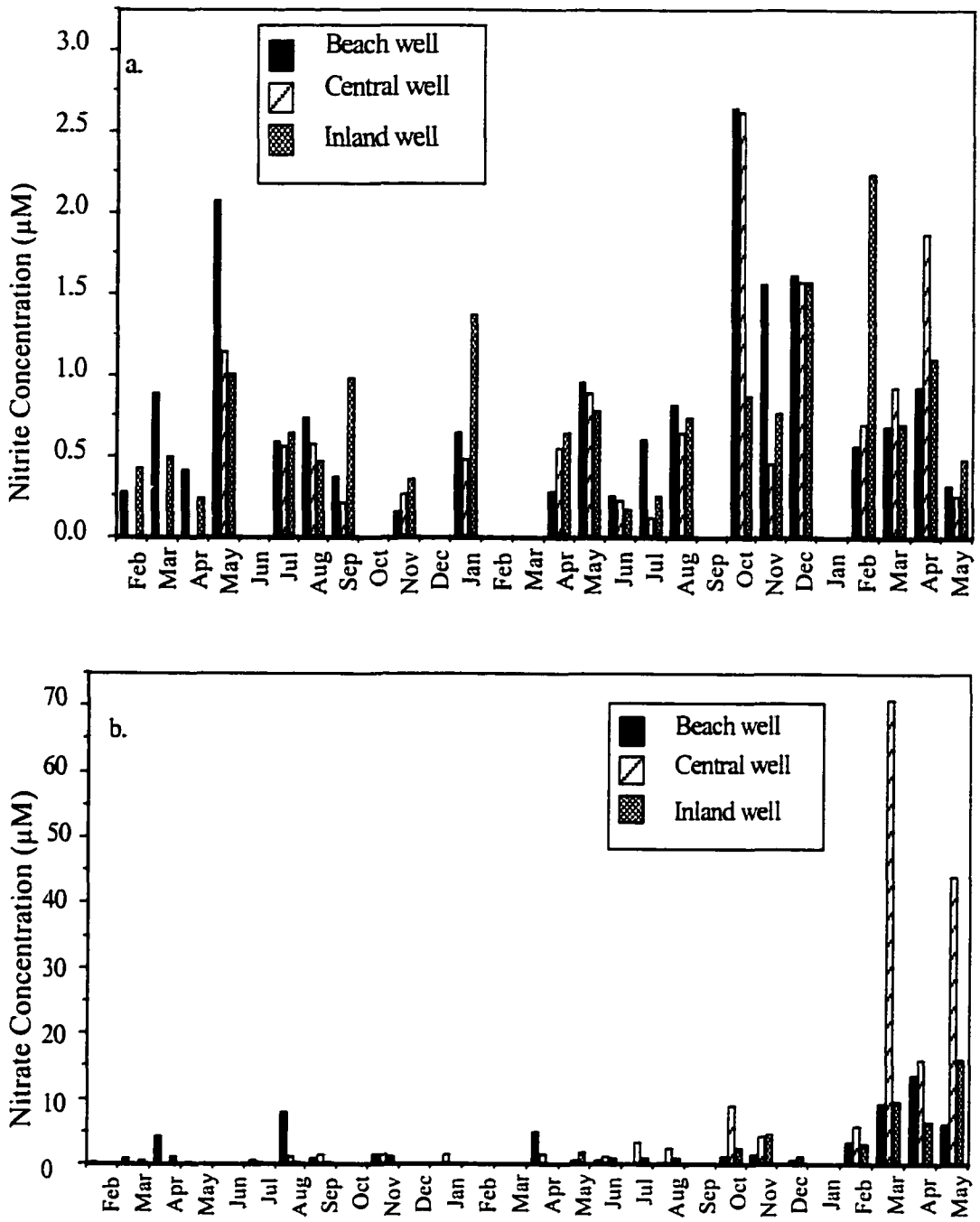

Fig. 14. Shallow groundwater nutrient concentrations: a.) nitrite, b.) nitrate, and c.) ammonium for all samples collected from February 1996 to May 1998.

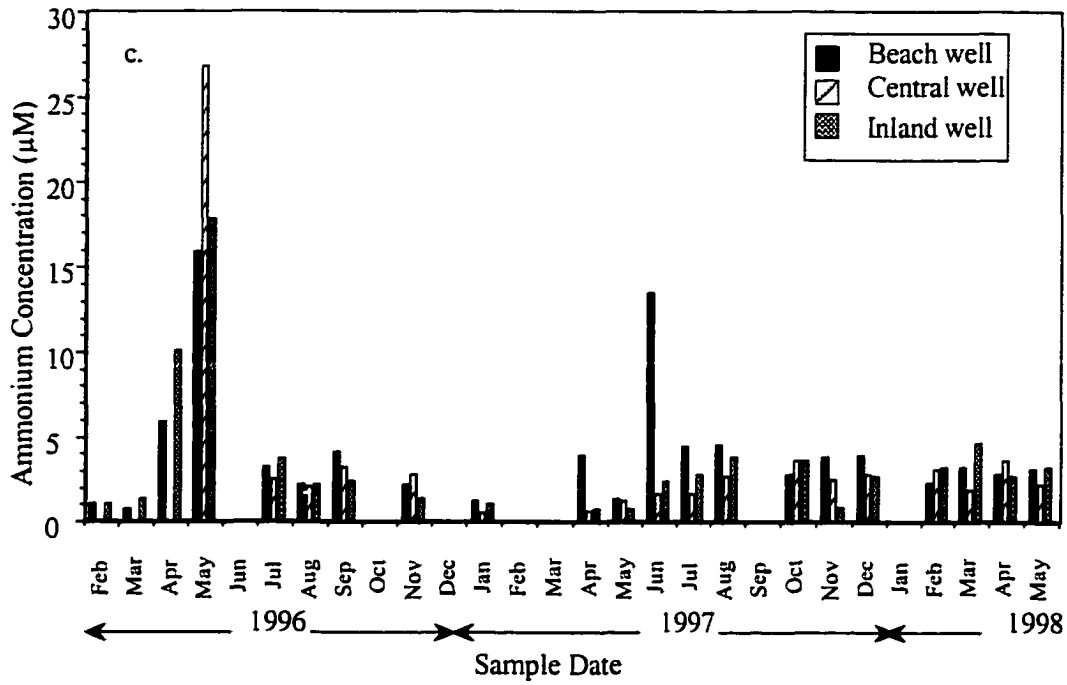

Fig. 14 Continued.

Maximum nitrate concentrations occurred in the central well on March 1998 with measurements reaching 70.85 µM while minimum concentrations were determined to be below detection limits in several of the shallow groundwater wells on various sampling dates (Fig. 14-b).

Overall, it is difficult to interpret any apparent seasonal trends in the nitrite fractions, although, the range of NO_2^- concentrations are much smaller than those determined for both ammonium and nitrate concentrations throughout the study. Nitrite concentrations (Fig. 14-c) ranged between 0.10 – 2.64 µM over the sampling period with an average concentration of 0.72 µM for the entire study. Concentrations of NO_2^- were generally greatest in beach wells, directly adjacent to Greens Creek, as compared to both the inland and central shallow groundwater wells. However, inland wells typically had greater NO_2^- concentrations than the central wells over the sampling period. Maximum

nitrite concentrations occurred in the beach well on October 1997 with measurements reaching 2.64 μM while minimum concentrations were determined to be 0.13 μM in the central groundwater well on July 1997.

In addition to the determinations of dissolved inorganic nitrogen species in the sub-surface shallow groundwater wells, PO_4^{3-} concentrations were also measured. Phosphate concentrations also varied among sampling dates with no evident seasonal trends (Fig. 15). Overall, concentrations were much greater from May 1997 to May 1998 as compared to all preceding sampling dates. Phosphate concentrations measured from below detection limits to 5.23 μM over the sampling period with maximum concentrations occurring in October 1997. Concentrations of PO_4^{3-} were generally greatest in beach wells, directly adjacent to Greens Creek, with concentrations decreasing as distance from the creek increased. Freshwater systems are typically P-limited while marine systems often have adequate concentrations of available P; therefore, these results provide evidence of tidal pumping into these sub-surface shallow groundwater wells. Tidal pumping occurs in the tidally active region of the aquifer and is a process by which groundwater flow is controlled by the tidal fluctuations on the creek's surface. The variations in tidal elevations promote fluctuating groundwater table elevations and thus alter discharge rates into Greens Creek. In addition, tidal pumping processes allow for the mixture of fresh and saline water thus permitting available P to enter the groundwater aquifer.

Sub-surface shallow groundwater discharge may contribute a significant fraction of both N and P demanded by phytoplankton directly to Greens Creek through the creek's banks. In order to investigate the nutrient contribution available to the phytoplankton community in Greens Creek, mean hourly and yearly fluxes were calculated for all measured nutrient species with results shown in Table 16. Average loading rates were determined using an average discharge rate of 2.0 L m^{-2} $hour^{-1}$ based on the results of a groundwater discharge study conducted on the Eastern Shore by Robinson et al. (1997). The results of this study indicate that nitrate was the predominate DIN-species loaded to the marine portion of Greens Creek's followed by ammonium with phosphate also being of significance. Mean hourly loading rates for dissolved inorganic nitrogen species

equating to 0.612, 0.147, and 0.066 mg m^{-2} $hour^{-1}$ for NO_3^-, NH_4^+, and NO_2^- respectively were determined. In addition, percent compositions of the total sub-surface shallow groundwater discharge for each nutrient species (Table 16) was also determined with the following results: (56.8%) nitrate; (13.6%) ammonium; (23.4%) phosphate and (6.1%) nitrite. Total DIN accounted for 76.6% of the total measured nutrient composition entering Greens Creek through shallow groundwater discharge. On a yearly basis, groundwater contributes a total of 3613.5 mg m^{-2} DIN $year^{-1}$ (4.91 (*10^3) moles DIN $year^{-1}$ and 1103.8 mg m^{-2} P $year^{-1}$ (6.57 (*10^2) moles P $year^{-1}$.

TABLE 16. Mean hourly (mg m^{-2} $hour^{-1}$) and yearly (mg m^{-2} $year^{-1}$) loading rates of N and P components of shallow groundwater discharge are presented. Percent compositions of the total groundwater flux for each nutrient species are also provided.

Loading Rate	NH_4^+	NO_3^-	NO_2^-	Total DIN	PO_4^{3-}
Mean Hourly Flux (mg m^{-2} $hour^{-1}$)	0.147	0.612	0.066	0.825	0.252
Yearly Flux (mg m^{-2} $year^{-1}$)	643.8	2680.6	289.1	3613.5	1103.8
% Composition of the Total Flux					
	13.6	56.8	6.1	76.6	23.41

Reservoir Discharge

In addition to measuring the nutrient content and discharge of sub-surface shallow groundwater, the reservoir located at the head of Greens Creek was also investigated as a freshwater source of nutrients for marine phytoplankton production. Similar to the results for shallow groundwater, there is a great deal of variation in reservoir nutrient concentrations over the sampling period. Only the DIN species, NO_3^-, NH_4^+, and NO_2^-, were measured in the reservoir discharge along with phosphate concentrations. No reservoir nutrient data is available from September and December 1996; March 1997; and January 1998. Total dissolved inorganic nitrogen concentrations, measured as the sum of NH_4^+, NO_3^- and NO_2^-, showed great variations over the sampling period with concentrations ranging from a minimum of 3.77 μM (November 1996) to a maximum of 708.01 μM (May 1998). Overall, reservoir DIN concentrations were greatest during the 1998 sampling months as compared to the previous years. The mean DIN concentration for the 22 month sampling period equated to 161.74 μM which is significantly greater (6 times) than the 28 month average shallow groundwater contribution (25.18 μM).

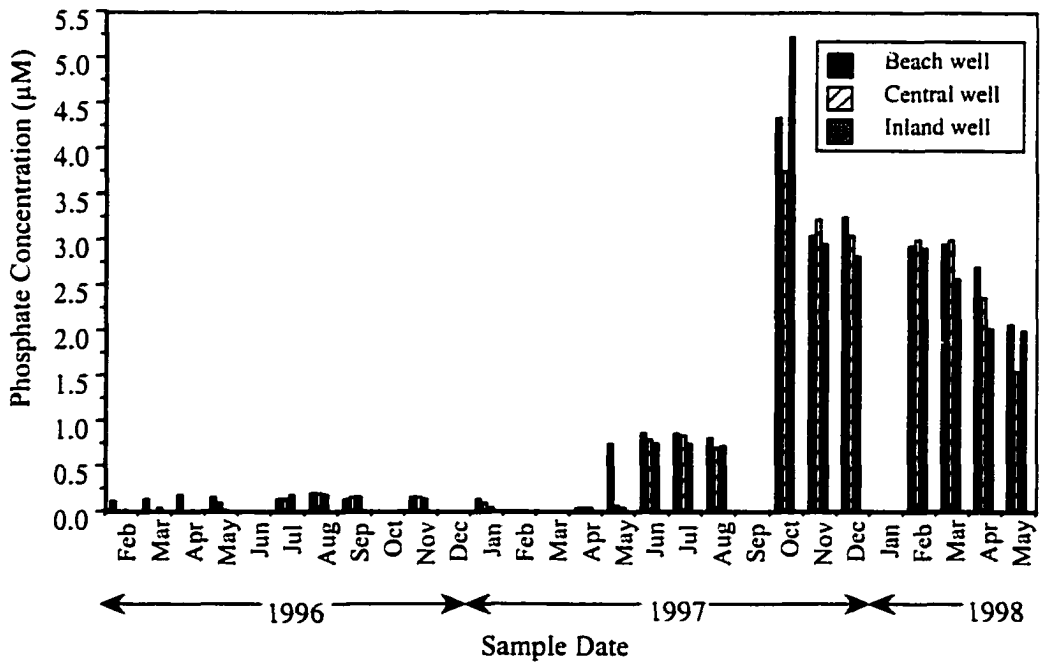

Fig. 15. Phosphate concentrations of sub-surface groundwater for all samples collected from February 1996 to May 1998.

Dissolved inorganic nitrogen inputs in the collected reservoir samples were primarily characterized by nitrate (99.99%) with ammonium (<0.001%) and nitrite concentrations (<0.001%) being of little significance. Concentrations of NO_3^- were greatest during the 1998 sampling periods as compared to all previous sampling dates, although, there is some evidence of a slight increase in NO_3^- concentrations from 1996 to 1998 (Fig. 16). Nitrate concentrations (Fig. 16) ranged from below detection limits to 706 μM over the sampling period with maximum concentrations occurring during spring months (March - May 1998). The mean nitrate concentration equated to 159.14 μM. There is evidence of a seasonal NO_3^- trend in which winter months are characterized by low concentrations and increasing to maximum concentrations as summer months approach. Once maximum values are reached during summer months, concentrations begin to decrease in the fall months and decrease further to minimum concentrations in the winter.

There appears to be a seasonal ammonium trend in the reservoir discharge from the spillway with maximum measurements occurring in late summer and early fall (August through October) of the year. Ammonium concentrations were consistently greater during the late summer and early fall of 1996 as compared to the following sampling year, although the maximum measured ammonium concentration occurred in September 1997. Ammonium concentrations in the reservoir samples (Fig. 17) ranged from a low concentration of 0.51 μM to a high concentration of 6.24 μM over the sampling period and are significantly less than concentrations determined for nitrate. Maximum ammonium concentrations occurred on September 1997 with measurements reaching 6.24 μM while minimum concentrations were measured on April 1997 at 0.51 μM. Over the study, the mean ammonium concentration for the 22 month sampling period equated to 1.97 μM. This reservoir mean concentration is approximately 1.5 times less than the average NH_4^+ concentration determined for sub-surface shallow groundwater contribution.

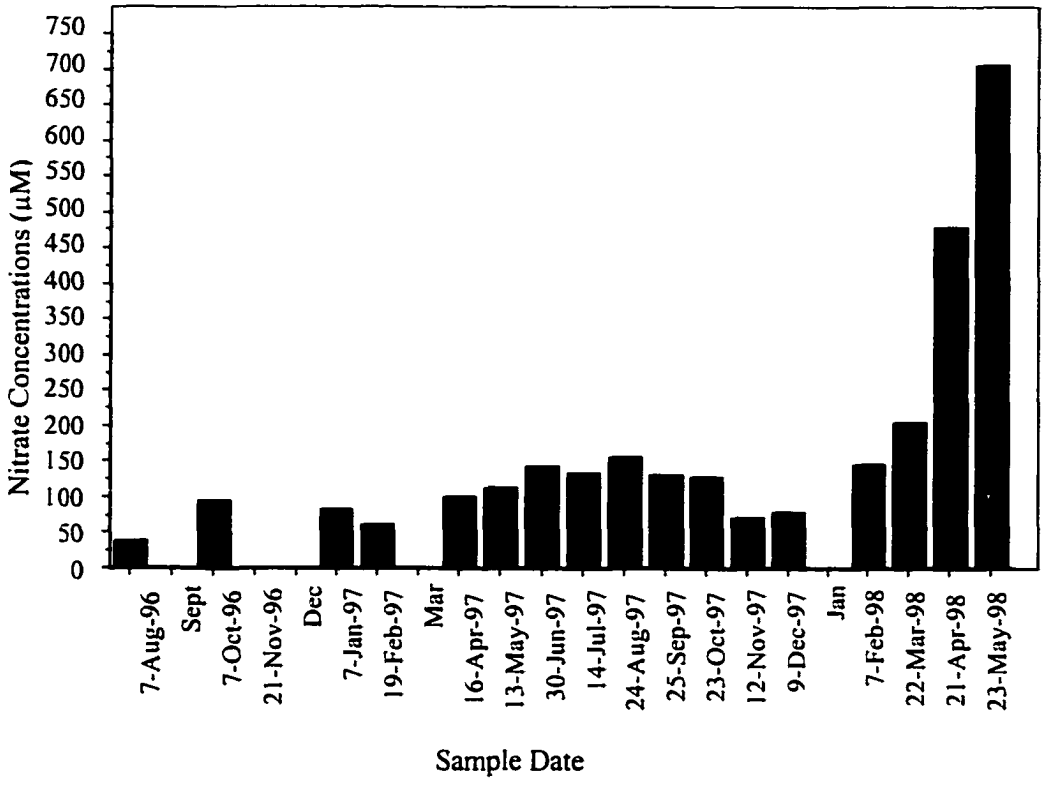

Fig. 16. Greens Creek reservoir nitrate concentrations for all samples collected from August 1996 to May 1998.

No apparent seasonal patterns in the nitrite component was identified, although, the range of NO_2^- concentrations are much smaller than those determined for the previously described ammonium and nitrate concentrations throughout the study. Nitrite concentrations (Fig. 18) generally ranged between 0.23 – 1.79 µM over the sampling period with an average concentration of 0.63 µM for the entire study. Concentrations of NO_2^- were greatest on September 1997 (1.79 µM) and correspond to the maximum measured ammonium concentration observed on that sample date. The minimum concentration was determined to be 0.23 µM on February 1997. Although NO_2^- concentrations are very low, nitrite is still an important component of the available

reservoir N since it serves as the intermediate N-species in ammonification and denitrification processes.

In addition to the determinations of dissolved inorganic nitrogen concentrations (NO_3^-, NH_4^+, and NO_2^-) in the Greens Creek reservoir, PO_4^{3-} concentrations were also measured. Phosphate concentrations also varied greatly among sampling dates with no evident seasonal trends (Fig. 19), similar to measured nitrite determinations. Overall, PO_4^{3-} concentrations were much greater in the fall and winter months of 1997 through the end of the study (May 1998) as compared to all preceding sampling dates.

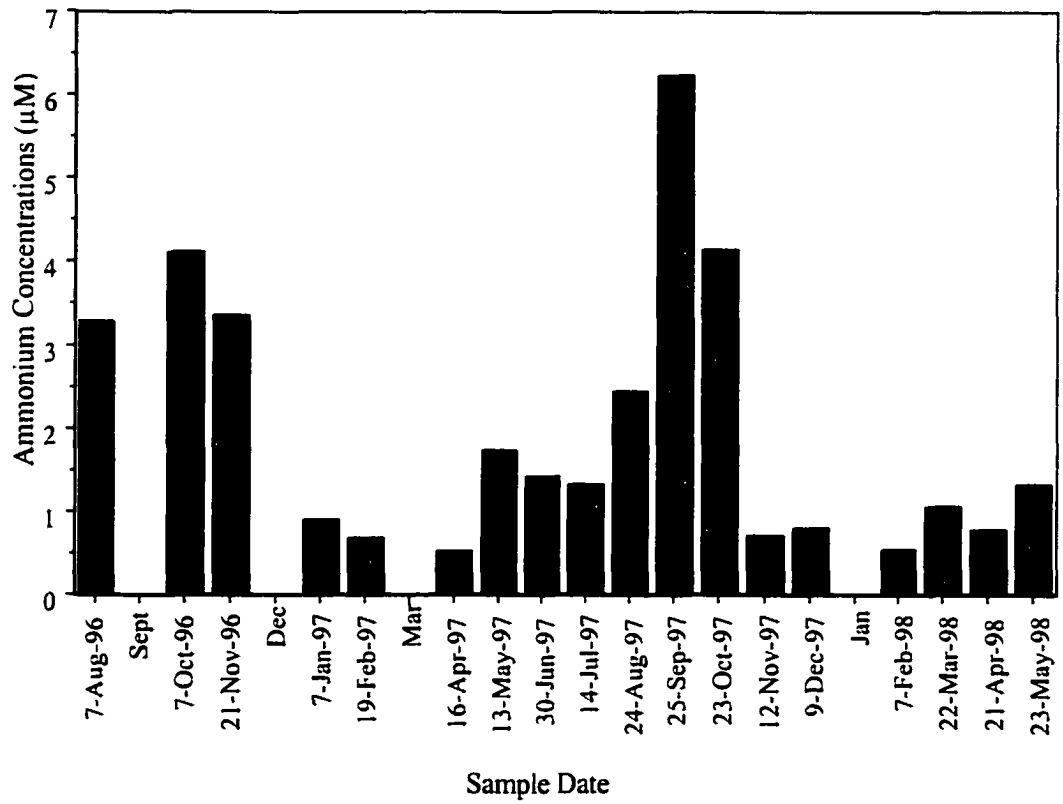

Fig. 17. Ammonium concentrations for all samples collected from August 1996 to May 1998 at the Greens Creek reservoir.

Phosphate concentrations measured from essentially 0 to 3.71 μM over the sampling period with maximum concentrations occurring in October 1997 similar to results determined for the sub-surface shallow groundwater wells. The mean phosphate concentration for the 22 month sampling period was 1.25 μM.

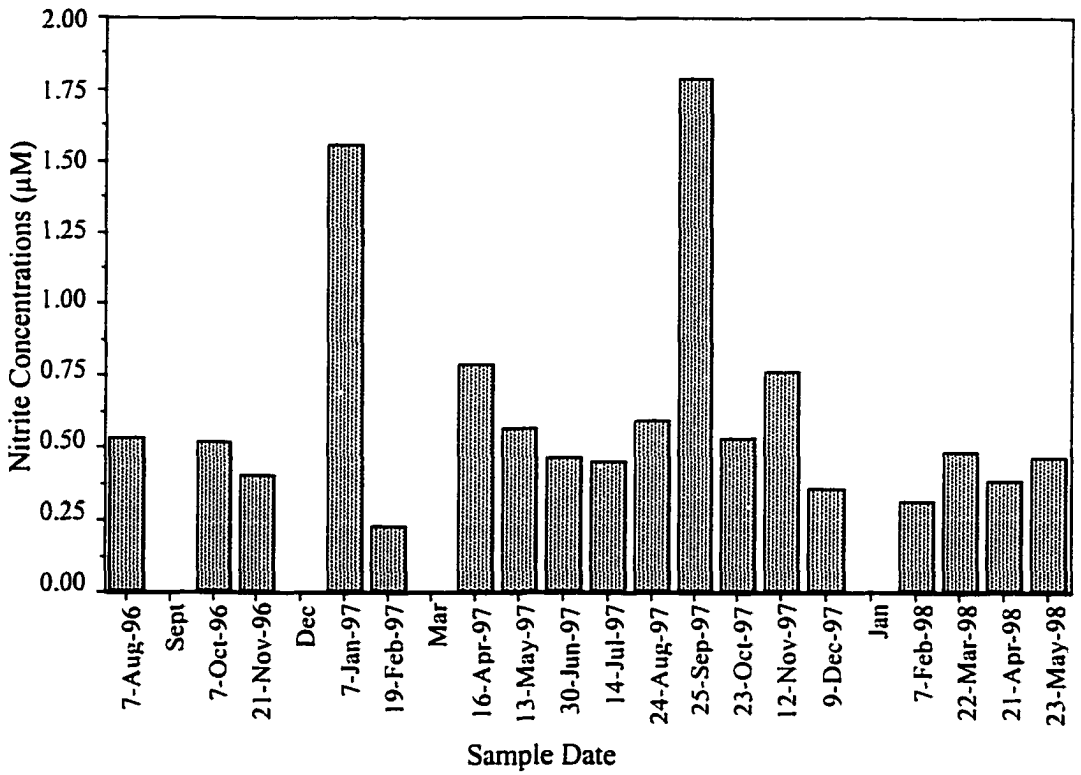

Fig. 18. Greens Creek reservoir nitrite concentrations for all samples collected from August 1996 to May 1998.

The contribution of nutrient rich freshwater through the reservoir spillway may contribute a significant fraction of both N and P required for phytoplankton growth directly to Greens Creek. Mean hourly and yearly fluxes were calculated for all measured reservoir nutrient species in order to determine the reservoir's nutrient contribution (Table 17). Average loading rates were determined using an average discharge rate of 3.39 $m^3 s^{-1}$ based on the spillway current velocity measurements. The

results of this study indicate that nitrate was the primary DIN-species loaded to the marine portion of Greens Creek by the spillway with phosphate also being of great importance. Mean hourly loading rates for dissolved inorganic nitrogen species equating to 5.69 ($*10^7$), 56.0, and 46.4 mg m^{-2} $hour^{-1}$ for NO_3^-, NH_4^+, and NO_2^- respectively were determined. In addition, percent compositions of the reservoir discharge for each nutrient species (Table 17) was also determined with the following results: 99.99% nitrate; 0.003% phosphate; <0.001% ammonium and <0.001% nitrite. Total DIN accounted for greater than 99.99% (1.73 ($*10^7$) moles DIN $year^{-1}$) of the total measured nutrient composition entering Greens Creek through the reservoir spillway.

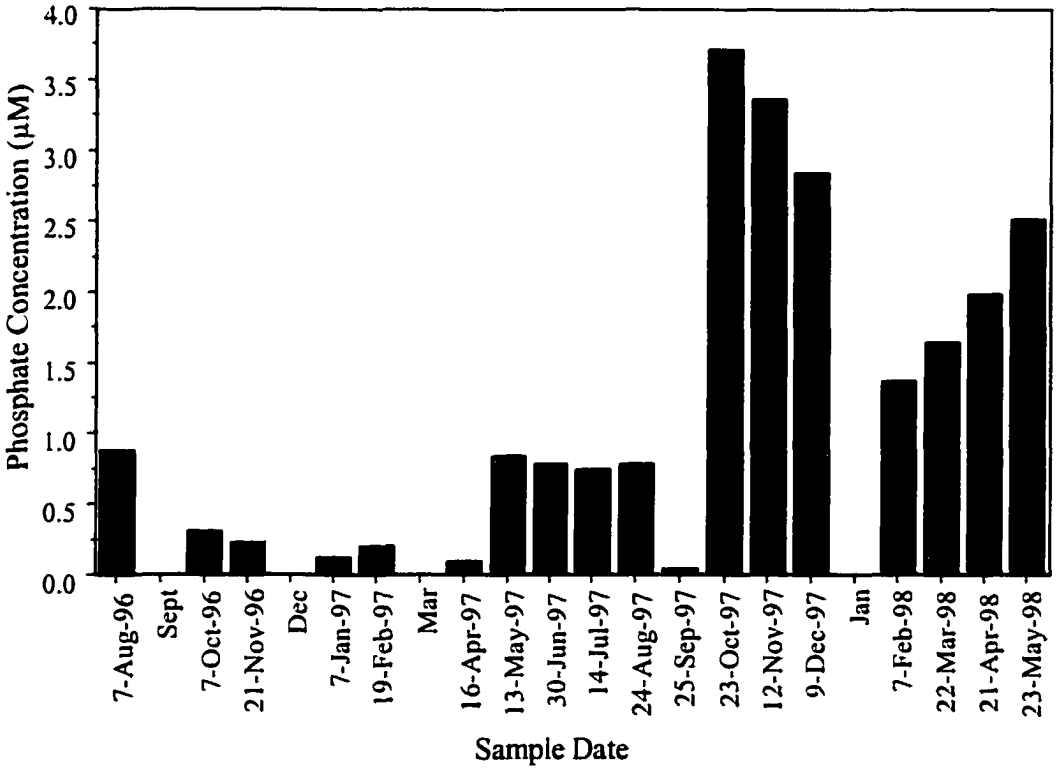

Fig. 19. Greens Creek reservoir phosphate concentrations for all samples collected from August 1996 to May 1998.

TABLE 17. Mean hourly (mg m^{-2} $hour^{-1}$) and yearly loading rates (mg m^{-2} $year^{-1}$) of N and P components of reservoir discharge are presented. Percent compositions of the spillway flux for each nutrient species are also provided.

Loading Rate	NH_4^+	NO_3^-	NO_2^-	Total DIN	PO_4^{3-}
Mean Hourly Flux (mg m^{-2} $hour^{-1}$)	56.0	5.69 (*10^7)	46.4	5.69 (*10^7)	1904
Yearly Flux (mg m^{-2} $year^{-1}$)	4.91(*10^5)	4.98(*10^{11})	4.06(*10^5)	4.98(*10^{11})	167(*10^5)
% Composition of the Total Flux					
	<0.001	99.99	<0.001	99.99	0.003

Dissolved inorganic nitrogen inputs from the reservoir discharge into Greens Creek are characterized as nitrate-rich (>99.99%) with ammonium and nitrite concentrations contributing very little to the total available inorganic N. Winter months are characterized by low NO_3^- reservoir concentrations increasing to maximum concentrations as summer months approach. Once maximum values are reached during summer months, concentrations begin to decrease through the fall months back to minimum concentrations in the winter. This seasonal pattern coincides with the elevated nitrate levels reported in the previously discussed atmospheric deposition events during summer months. Reservoir nutrient composition and discharge rates are governed by the surface flow in the upland freshwater portion of Greens Creek that is fed primarily by nitrate-rich groundwater and episodic rainfall events.

Hydrographic Parameters

Hydrographic information such as surface temperature, salinity and light transmissions through the water-column were measured at the time all water quality samples were collected. Temperature of the water column is an important physical factor in estuaries as it exerts an influence on many physical, chemical and biological events occurring within the system. For instance, water temperature controls the rates at which many chemical and biological processes take place. Over the study period (May 1996 through May 1998) surface water temperatures varied only slightly (+/- 1 °C) among the six stations on the Greens Creek transect (Fig. 2); therefore, surface temperatures were averaged over the entire transect to yield monthly values. As expected, surface water temperatures were warmest during the summer months (July – August) with coldest surface temperatures occurring in the winter months (November – January) (Fig. 20). Surface temperatures were measured between a minimum of 5.68 °C (December 1997) to a maximum of 28.66 °C (July 1997), values which range within the normal seasonal water temperatures for this area.

Accompanying surface water temperature measurements, surface salinity values were also recorded throughout the study. Surface salinity among the six stations of the transect varied significantly more than temperature measurements due to the large variations in freshwater discharge and proximity of the stations along the transect to the reservoir spillway, the primary source of freshwater to Greens Creek. Among transect stations, there are seasonally varying mixtures of fresh and seawater occurring at each station. In Figure 23, the station locations as previously shown in Figure 2 are now graphically represented as distance downstream from the reservoir spillway. The reservoir spillway, with a downstream distance equal to zero kilometers, always has a salinity of zero since this is a constant source of freshwater to Greens Creek. Additionally, stations 3B, 3A, 3, 4 and 5 have corresponding distances from the reservoir spillway equal to 0.75 km, 1.45 km, 2.25 km, 3.15 km and 4.0 km respectively. In general, the apparent pattern of salinity shows an increase in salinity as distance along the transect increases from the reservoir spillway for all sampling dates.

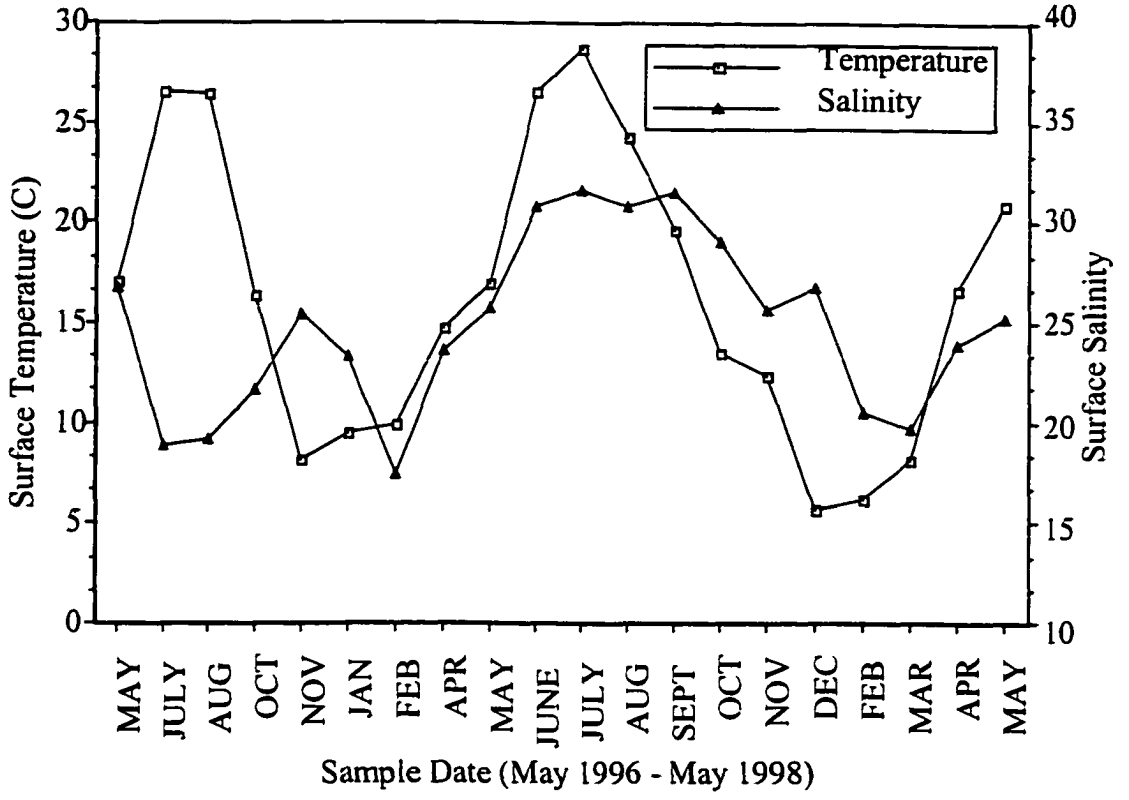

Fig. 20. Seasonal variations of surface temperatures (°C) and surface salinity measurements over the sampling period (May 1996 – May 1998).

In order to graphically decipher wet and dry periods throughout the sampling period, surface salinity measurements for all six stations were averaged over the entire transect. Surface salinity (Fig. 21) for the Greens Creek transect showed large variations with measurements ranging from 17.44 (February 1997) to 31.62 (July 1997) depicting apparent seasonal variations in freshwater inputs. In general, wet periods are characterized by lower surface salinity in conjunction with increased rainfall volumes. Dry periods, on the other hand, are characterized by higher surface salinity in conjunction with decreased volumes of rainfall. Rainfall volumes represented in Figure 22 show apparent alterations between wet and dry periods over the sampling period although there

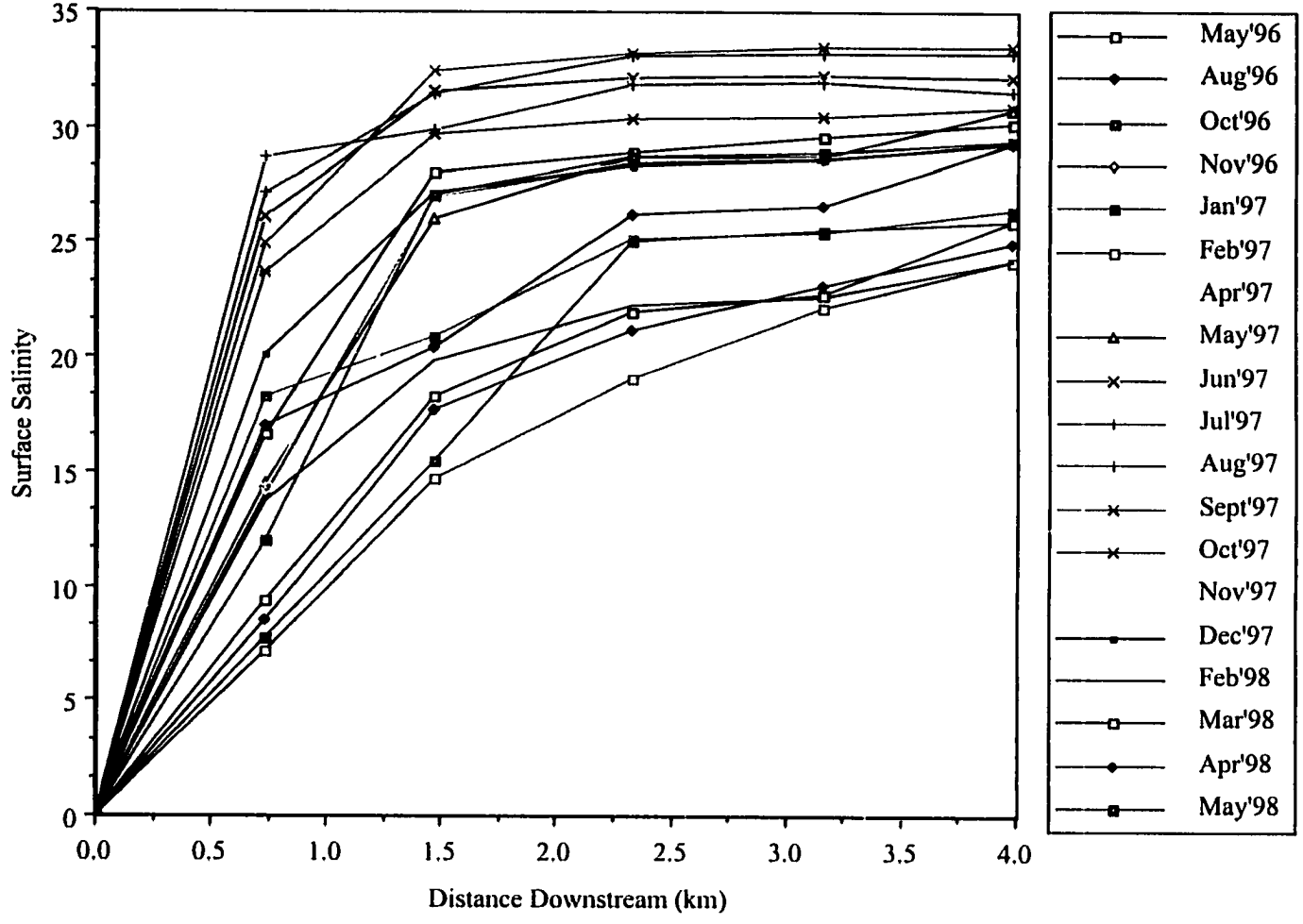

Fig. 21. Surface salinity measurements compared to distance downstream of the reservoir spillway for all sampling periods (May 1996 – May 1998). Station 3B, 3A, 3, 4 and 5 correspond to distances equal to 0.75 km, 1.45 km, 2.25 km, 3.15 km and 4.0 km respectively.

is no apparent seasonal or monthly pattern associated with wet and dry periods. Surface temperature and salinity measurements generally show similar patterns over the sampling period. For example, increased surface temperatures in summer also show increased salinity corresponding to periods of decreased freshwater input.

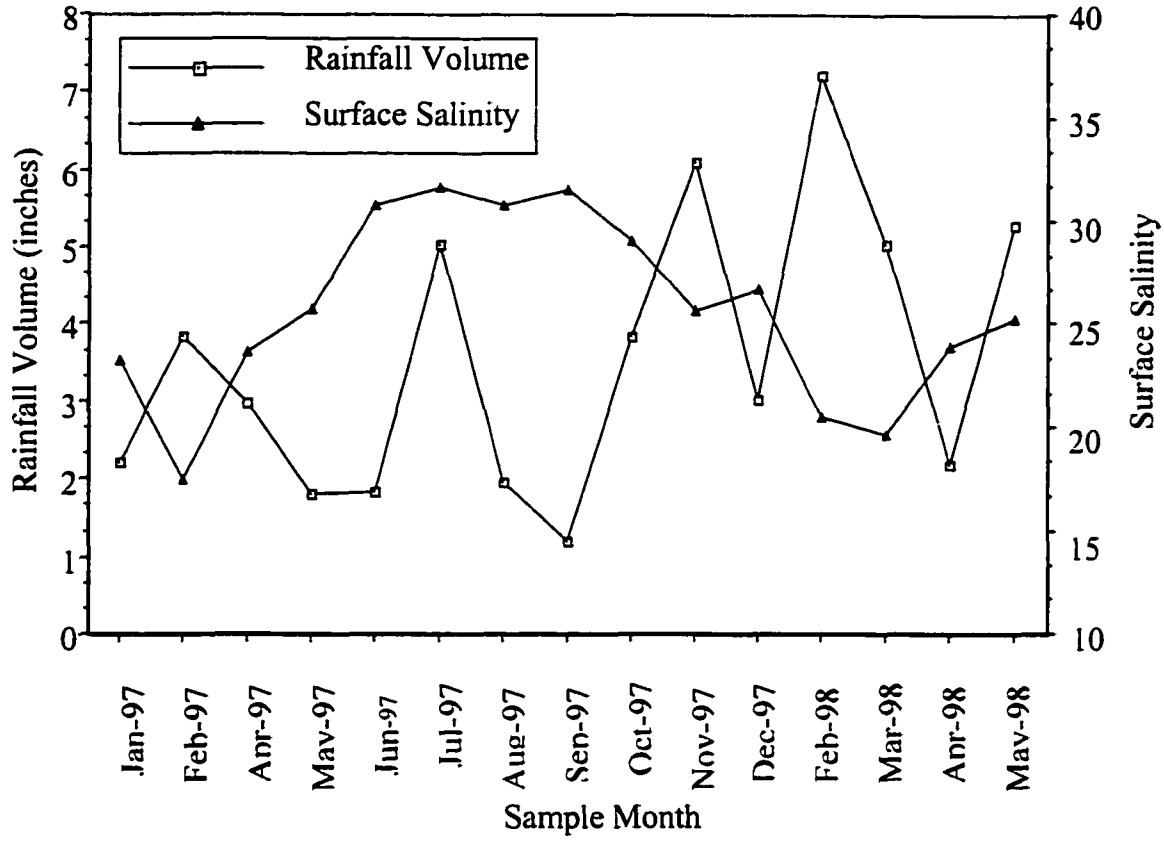

Fig. 22. Surface salinity measurements compared to seasonal variations in rainfall volume (inches) to determine wet and dry periods (May 1996 – May 1998).

In addition to surface water temperature and salinity measurements, light is also an important factor of phytoplankton research. Solar radiation is not simply absorbed by plants during photosynthesis but is also a driving force in the conversion of inorganic to organic compounds which drives their rate of production within the water column. Light availability in the water-column is regulated primarily by incident light, suspended

particulate matter, and the depth of the surface mixed layer. Photosynthetically active radiation (PAR), or visible light with wavelengths of 400 - 700 nanometers (nm), was measured at each station of the transect throughout the study period in 0.5 meter intervals from the water's surface to the maximum water column depth. Light extinction through the water-column is most often described as the exponential decrease of light with increasing depth and is represented by the light extinction coefficient (k). Light extinction coefficients were calculated for all sample dates and varied greatly with values ranging from 0.74 to 3.27 per station throughout the study period with all light extinction coefficient values shown in Table 18. Light extinction through the water-column is affected by many factors including the amount and particulate size of colored, dissolved and organic material in the water and also by the concentration of chlorophyll contained in phytoplankton and plant debris. The light coefficient values show no apparent seasonal trends throughout this study period; although, the highest k values were generally associated with station 3A and the lowest k values generally associated with station 3. These results implicate Greens Creek as a coastal system associated with high suspended sediment concentrations that strongly attenuate light and possibly acts as a constraint on phytoplankton growth.

Photosynthetically active radiation measurements at stations 5 (located in the Machipongo River) and 3 (located in Greens Creek) showed the largest variations in k values as compared to other stations along the transect. Station 5 has light extinction coefficient values ranging from 0.92 to 3.27 while station 3 has k values ranging from 0.74 to 3.17. Based on the water-column PAR measurements at stations 5 and 3, photic depths were also determined at these stations. The photic depth of a water-column is the depth at which only 1% of the surface irradiance is available. Station 5, located outside of Greens Creek in the Machipongo River, is the deepest of the water-column stations with a low tide depth of approximately 16 meters and a mean photic depth of about 2 meters (+/- 0.5 m). On the other hand, station 3, located near the entrance of Greens Creek, has a shallower water-column with a low tide depth of about 2 meters and a mean photic depth of 1.3 meters (+/- 0.3 m).

TABLE 18. Light extinction coefficients (k) determined for all stations along the Greens Creek transect throughout the sampling period (May 1996 – May 1998). Average attenuation coefficients for each station as well as maximum and minimum values are also given.

	Station				
Sample Date	5	4	3	3A	3B
29-May-96	1.79	na	1.39	1.68	1.28
15-Jul-96	1.75	na	3.17	1.94	na
7-Aug-96	2.15	na	1.60	1.47	2.64
7-Jan-97	1.12	0.96	1.30	1.08	1.08
19-Feb-97	1.19	1.34	1.46	1.58	1.96
4-Apr-97	0.92	1.28	1.42	1.31	na
14-May-97	1.03	0.98	0.88	1.47	1.02
30-Jun-97	2.43	1.94	1.12	3.13	2.60
15-Jul-97	2.13	1.55	1.44	2.34	1.94
24-Aug-97	1.60	1.68	1.39	2.12	1.98
9-Sept-97	1.17	0.88	0.74	1.57	1.63
23-Oct-97	1.34	1.48	1.20	1.61	2.15
12-Nov-97	1.74	0.87	0.92	1.03	2.77
7-Feb-98	3.27	2.01	1.91	2.02	1.74
22-Mar-98	1.49	1.62	1.45	1.98	2.04
21-Apr-98	2.00	0.95	0.84	3.23	na
23-May-98	1.49	1.49	1.66	1.98	na
Average k	1.68	1.36	1.40	1.86	1.91
Maximum k	3.27	1.94	3.17	3.23	2.77
Minimum k	0.92	0.87	0.74	1.03	1.02

"na" denotes no data is available

Phytoplankton Photopigments

The primary photopigment chlorophyll *a* was measured at all stations along the Greens Creek transect. Chlorophyll *a* concentrations provide a wealth of information regarding phytoplankton communities. Photopigment concentrations not only provide quantifiable estimates of phytoplankton abundance but also serve as an indicator of phytoplankton health within the system.

Over the study period (May 1996 - April 1998) there was a seasonal pattern in total chlorophyll *a* concentrations ([chl-a]) (Fig. 23). These results show the development of two peaks throughout the year with maximum [chl-a] occurring first during the early spring months (February) and again during the summer months (June – August). This trend was evident for all sampling years (1996 – 1998) of the study. The average [chl-a] was determined to be 8.50 $\mu g\ L^{-1}$ for all of the collected samples with concentrations ranging from as low as 0.46 $\mu g\ L^{-1}$ to as high as 32.84 $\mu g\ L^{-1}$ during peak conditions. The maximum measured [chl-a] was recorded to be 32.84 $\mu g\ L^{-1}$ at station 3B on April 21, 1998. Station 3B is the closest station to the reservoir spillway and April 1998 reservoir data reveals that nutrient concentrations, nitrate concentrations in particular were greatest during April 1998 as compared to the entire sampling period with a NO_3^- concentration of approximately 475 μM. More interestingly the minimum [chl-a] of 0.46 $\mu g\ L^{-1}$ occurred at two stations within Greens Creek on two sampling dates, November 1996 (station 3A) and November 1997 (station 3) when nutrient concentrations in the creek were low as compared to other sampling dates. Figure 24 shows the relationship between total chlorophyll-a and dissolved inorganic N throughout the sampling period. It is difficult to decipher a linear relationship from the data; thereby suggesting that factors other than DIN are responsible for the observed chlorophyll-a concentrations.

In addition to chlorophyll *a* measurements estimates of phaeophytin *a* were also determined. Phaeophytin *a* ([phaeo-a]) is the degraded form of chlorophyll and serves as a useful indicator of the health of the natural algal population. Therefore, the pigment

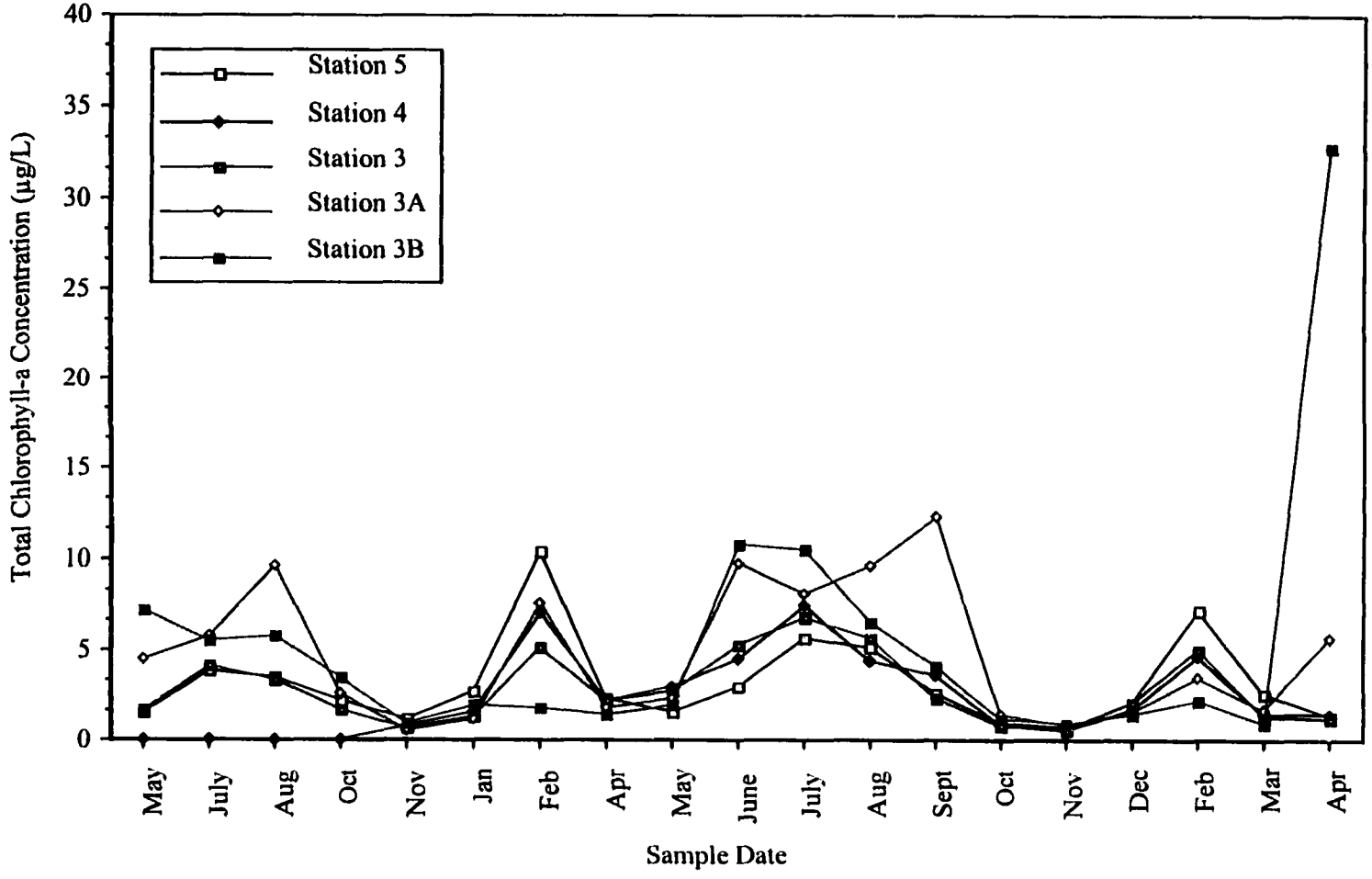

Fig. 23. Total chlorophyll *a* concentrations (µg/L) at all stations along the Greens Creek transect throughout the sampling period (May 1996 – April 1998).

composition of a population is an ideal indicator of the physical condition of the algal community. In order to determine growth stage of the algal populations throughout the Greens Creek transect, pigment ratios ([chl-a:phaeo-a]) were calculated to estimate the percent of degraded chlorophyll cells. The overall percent degradation and corresponding [chl-a:phaeo-a] ratios for all sampling events are shown in Table 19 and varied greatly over the study period. Percent degradation values (Table 19) are percentages averaged over all stations along the transect in order to examine any seasonal patterns in phytoplankton health. Percent degradation ranged from 32.31% to 65.97% with lower percentage values indicative of healthier phytoplankton cells. The opposite also holds true that higher percentages are indicative of senescent or degrading cells. Overall, healthiest cells are present during bloom conditions or periods of stimulated growth while there is an increase in cell degradation during winter months when production is at its lowest.

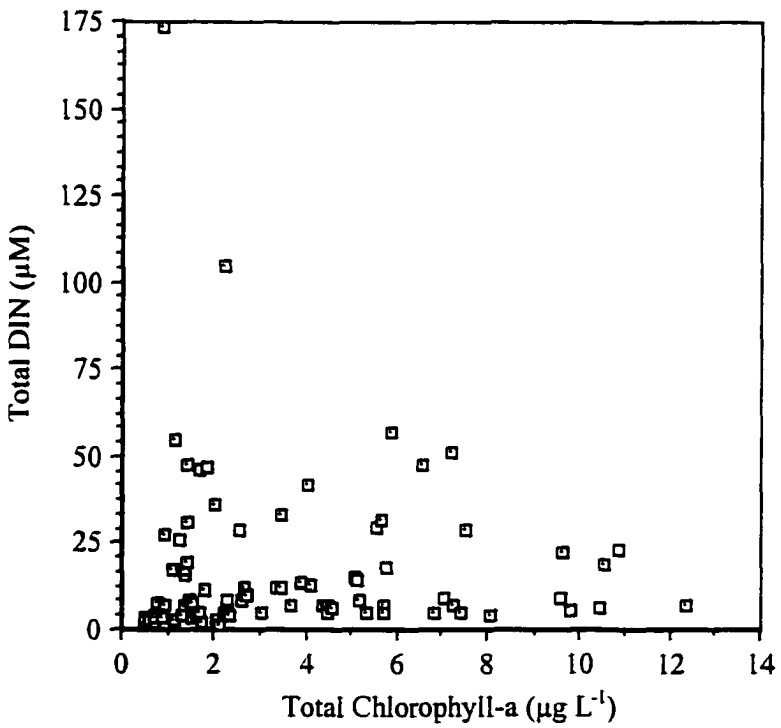

Fig. 24. The relationship between total chlorophyll-a (µg L^{-1}) and dissolved inorganic N (µM) throughout the sampling period.

TABLE 19. Mean percent degradation values calculated from [chl-a:phaeo-a] obtained at each station along the transect over the sampling period.

Sample Date	[chl-a:phaeo-a]	Percent Degradation (%)
Year 1996		
May 1996	1.50	41.04
July 1996	1.75	35.90
August 1996	2.09	33.54
October 1996	1.46	40.51
November 1996	0.72	57.15
Year 1997		
January 1997	1.21	45.87
February 1997	2.51	32.31
April 1997	1.24	44.62
May 1997	1.62	38.43
June 1997	1.86	35.98
July 1997	2.02	33.05
August 1997	1.98	34.05
September 1997	2.04	33.76
October 1997	0.61	58.04
November 1997	0.47	65.97
December 1997	1.81	34.91
Year 1998		
February 1998	1.84	36.02
March 1998	1.08	49.38
April 1998	3.48	35.99

In addition to analyzing total chlorophyll *a* concentrations for the Greens Creek transect, size fractionated chlorophyll concentrations were also measured at all stations. Size-fractionated chlorophyll *a* samples for total population and less than 20 μm fractions were measured in order to identify the size class of the algal population contributing the most to the total production occurring within this system. As previously discussed in this section, total chlorophyll *a* concentrations over the sampling period revealed the development of two blooms throughout the year. The first bloom occurred during the early spring months (February) and the second during the summer months (June through August). Chlorophyll levels are generally between 1 – 4 μg L^{-1} with higher concentrations during blooms (7 – 11 μg L^{-1}) as would be expected. This trend was evident for all sampling years (1996 – 1998) of the study. The same seasonal trend is apparent at the individual stations along the water column transect (Fig. 25 a-e) with the exception of station 4. There is no chlorophyll concentration data available at the water column station 4 for the sampling dates May 29, 1996, July 15, 1996, August 7, 1996 and October 22, 1996 although, the seasonal chlorophyll pattern is evident for the remainder of the sampling period.

Figures 25 (a-e) depict the total chlorophyll *a* fraction and corresponding less than 20 μm size fraction measured at each station over the sampling period. The less than 20 μm size fractions makes up a significant percentage of the total measured chlorophyll at all stations over the sampling period. This means that the composition of the phytoplankton community is dominantly composed of those species less than 20 μm in size (approximately 60 – 90%). These results indicate that phytoplankton species less than 20 μm in size constitute on average approximately 91% of the total phytoplankton production occurring within Greens Creek. A few sample dates were omitted from this analysis due to analytical errors in which the less than 20 μm size fraction was determined to have greater concentrations that the total chlorophyll fraction. The total chlorophyll *a* fraction and corresponding less than 20 μm size fraction values which were omitted from this research include station 5 (June 1997), station 5 (August 1997), station 3 (March 1998), station 3A (May 1996) and station 3B (March 1998).

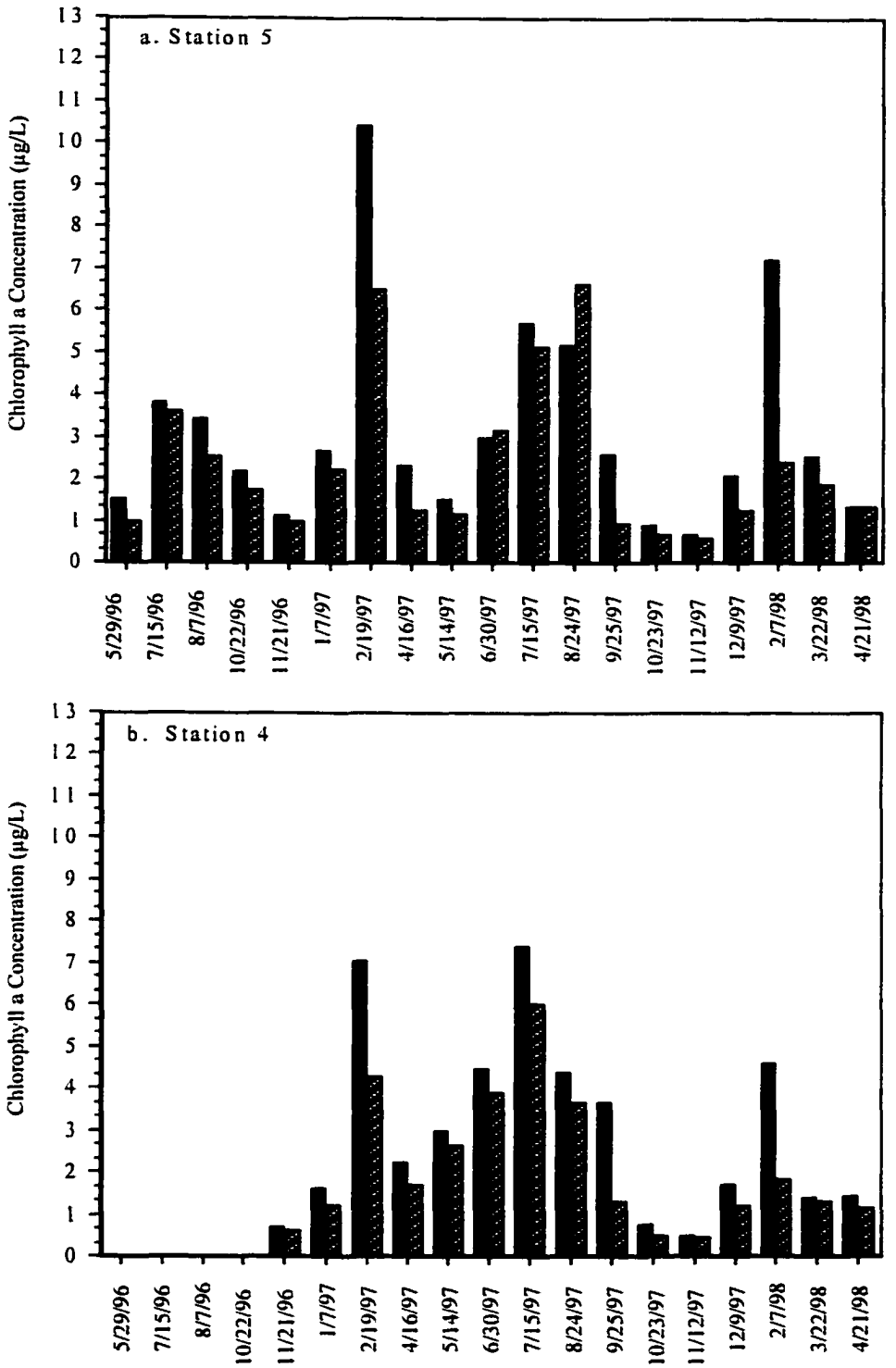

Fig. 25(a-e). Size fractionated chlorophyll *a* concentrations (µg L^{-1}): a.) station 5, b.) station 4, c.) station 3, d.) station 3A and e.) station 3B over the entire sampling period (May 1996 – April 1998). Total chlorophyll *a* is graphically represented by the solid bar with the less than 20 µm fraction represented by the striped bar.

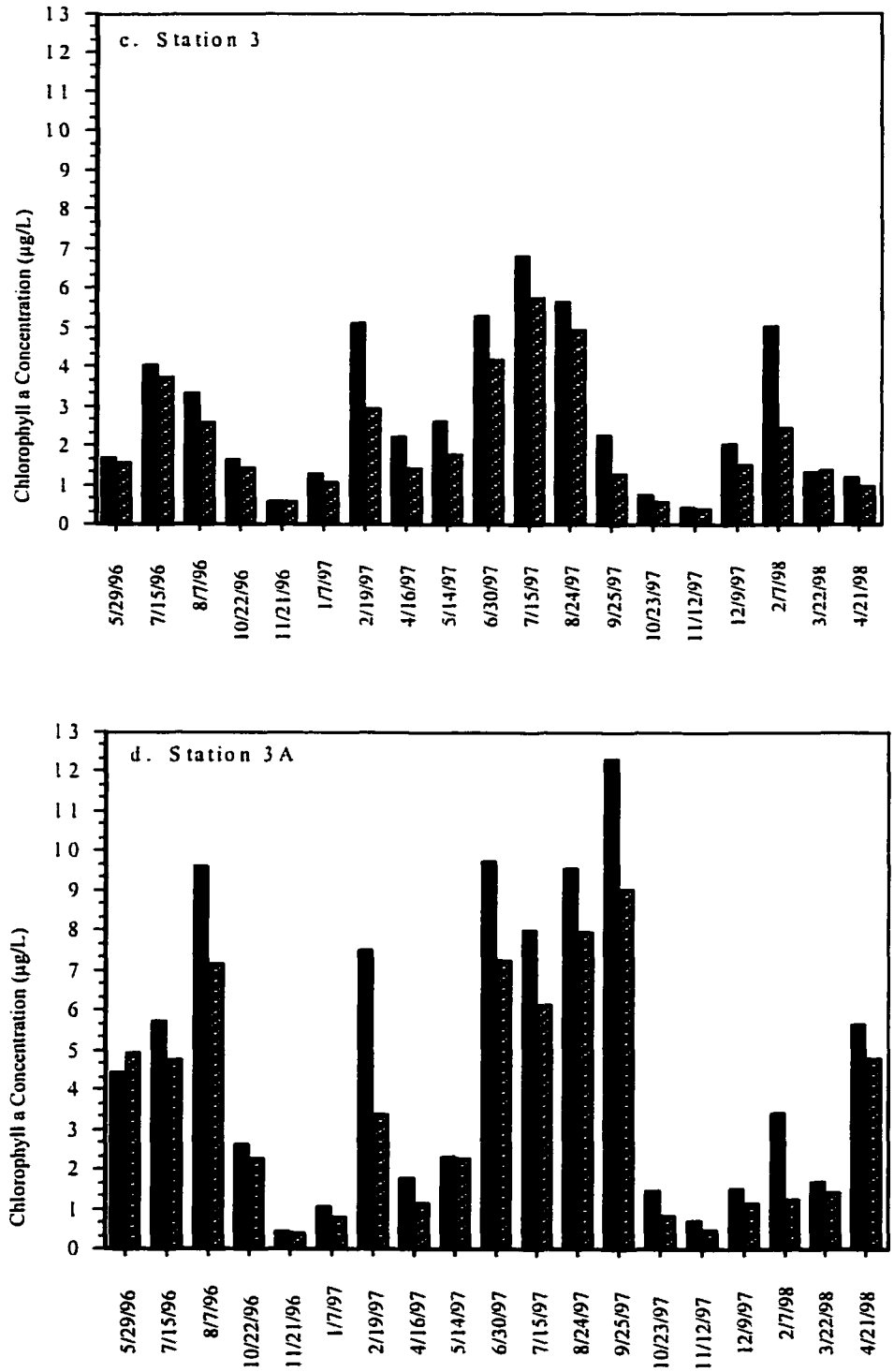

Fig. 25(a-e) Continued.

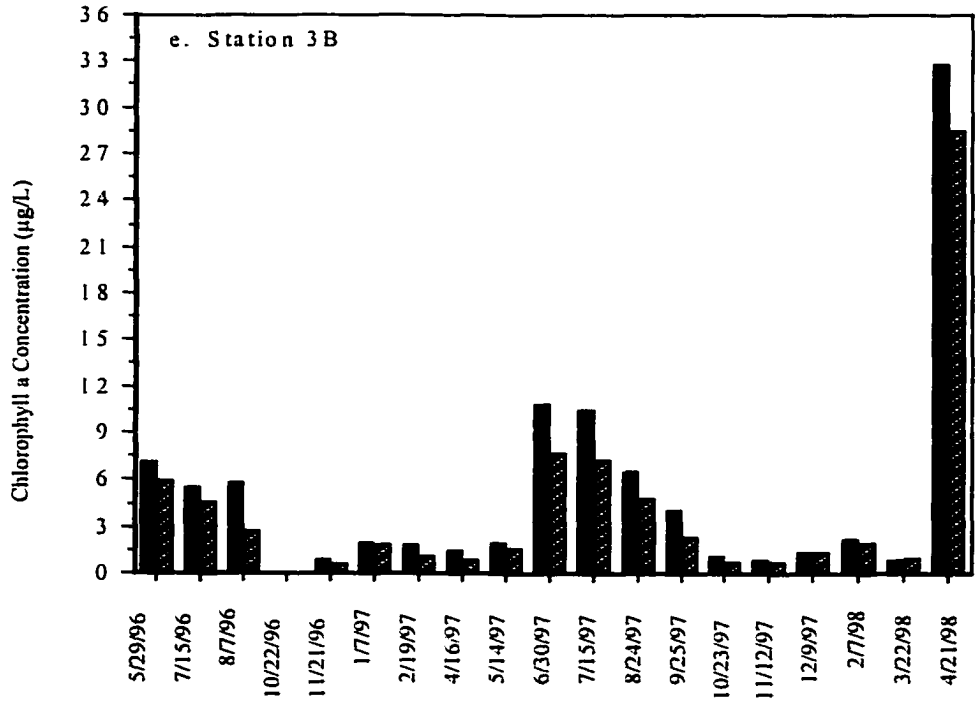

Fig. 25(a-e) Continued.

The results of this research show that a strong correlation exists between the less than 20 µm chlorophyll size fraction and total chlorophyll (Fig. 26) measured in natural phytoplankton assemblages. These results indicate that phytoplankton species less than 20 µm in size constitute on average approximately 91% of the total phytoplankton production occurring within Greens Creek.

Species identifications of preserved cell samples revealed that the less than 20 µm size class was composed primarily of species such as: *Leptocylindrus minimus, Thalassionema nitzschioides, Skeletonema costatum, Cryptomonas pseudobaltica* and a variety of other small diatoms. The larger species (greater than 20 µm) consisted of various diatoms including *Coscinodiscus* species, *Rhizosolenia setigera, Pleurosigma* species., *Corethron criophilum* and dinoflagellates such as *Heterocapsa triquetra, Gymnodinium splendens* and *Dinophysis* species.

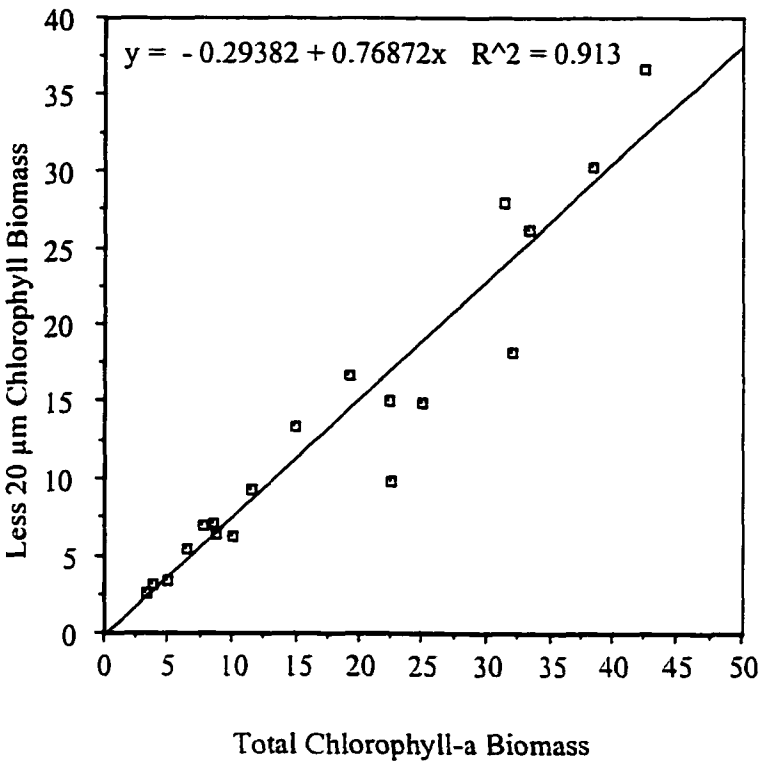

Fig. 26. Comparison of < 20 µm micron chlorophyll a fraction to total chlorophyll a determined from field collected biomass measurements along the Greens Creek transect.

Primary Production Model

In addition to measuring the quantitative biomass of the phytoplankton species in the Greens Creek watershed, a primary production model was also incorporated into this research. Historically, experimental work in large-scale mesocosms has concomitantly established a strong linear relationship between nutrient loading and phytoplankton biomass (Nixon and Pilson, 1983, Nixon et al., 1984, Keller, 1988). With this relationship in mind, the predictive ability of a model that includes both measurements of light availability and phytoplankton biomass is a useful tool for phytoplankton research. Phytoplankton biomass indirectly incorporates the effects of nutrient uptake rates, variations in growth rates and population structure in the model (Keller, 1988).

Unfortunately, primary production is not measured regularly in many coastal systems of the world. Researchers have shown that primary productivity in a variety of estuarine systems is highly correlated with phytoplankton biomass (measured as chlorophyll *a* concentrations) and an index of light availability in the photic zone (Cole and Cloern, 1987; Keller, 1988; Hinga et al., 1995). The premise of this model is that short term, or instantaneous, depth integrated primary production can be estimated very well by three factors: phytoplankton abundance; depth of the photic zone and the amount of incident light (Hinga et al., 1995). Primary production estimates can then be derived from the following equation (eqn. 5):

$$\text{Primary Production (P) (mg C m}^{-2}\text{ day}^{-1}\text{)} = B * Z_p * I_o \qquad \text{(eqn. 5)}$$

where B = phytoplankton abundance measured as chlorophyll *a* (mg chl-*a* m^{-3})

Z_p = photic depth (m)

I_o = surface irradiance (360° sensor) (E m^{-2} day^{-1})

Stations 5 and 3 of the transect were chosen to investigate primary productivity differences occurring at these two stations since these stations represent locations both outside (station 5) and within (station 3) Greens Creek. Based on the water-column PAR measurements, the average photic depth (Z_p) was determined to be 2.0 meters for station 5 with depths ranging from 1.5 – 3.5 meters throughout the sampling period. The average photic depth for station 3 was determined to be slightly shallower than station 5 with a Z_p = 1.3 meters and depths ranging from 1.0 – 2.0 meters. Station 3 has a much shallower water-column of about 2.0 meters as compared to station 5 which is located in a deep channel outside of Greens Creek with a maximum depth of approximately 16 meters. These PAR results show that at low tide, phytoplankton are able to utilize the entire water-column of station 3 while production is limited to the first few meters of the water-column at station 5. It is hypothesized that sediment exchange reactions may play a large role in phytoplankton dynamics at station 3 due to sediments supplying available nutrients to the shallow water-column.

This model assumes that phytoplankton chlorophyll *a* (B) is homogeneously distributed throughout the photic zone; therefore, the photopigment chlorophyll *a* samples were collected just below the water's surface (approximately 0.3 meters). Over the sampling period, station 5 statistically had the same total chlorophyll *a* concentrations as station 3 with mean concentrations equal to 3.42 (+/- 2.59) mg Chl-*a* m^{-3} and 3.07 (+/- 2.01) mg Chl-*a* m^{-3} respectively. However, station 5 generally had greater total chlorophyll *a* concentrations than station 3 on a per sampling date basis (Fig. 27). Overall, both station 5 and 3 show the same apparent seasonal trends with maximum chlorophyll concentrations occurring in the early spring – summer months and minimum concentrations in the late fall – winter months.

In addition to photic depth and biomass abundance, the final parameter required for the model is the measurement of surface irradiance. Surface irradiance values vary significantly over the course of the year due to several factors including angle of incidence, latitude and local climate. Surface irradiance was measured on each day of the sampling period with values ranging from as low as 102 to as high as 2088 $\mu E\ m^{-2}\ s^{-1}$. Overall, surface irradiance values were greatest during the summer months and lowest during the winter months, as one would expect. In order to estimate surface irradiance per day, an average yearly photic period of 10:14 (light:dark cycle) was used for the calculations.

The relationship between photic zone primary productivity and the parameters BZ_pI_o yielded large variations in daily production at both stations 5 and 3 (Fig. 28). Over the sampling period, station 5 statistically had the same modeled daily productivity as station 3 with mean values of 171.35 (+/- 165.51) mg C m^{-2} day^{-1} and 101.76 (+/- 97.76) mg C m^{-2} day^{-1} respectively. Station 5 generally had slightly greater values of primary production than station 3 on a per sampling date basis (Fig. 28) which is consistent with the fact that station 5 also had slightly greater values for all measured parameters. Overall, modeled data (Fig. 28) determined for both stations 5 and 3 show the same seasonal trends with maximum chlorophyll specific production occurring in early spring months for years 1997 and 1998 with the exception of an additional bloom occurrence during the summer (June and July) of 1997. Minimum production occurred in the late

fall months corresponding to when total chlorophyll *a* concentrations and surface irradiance measurements were generally the lowest.

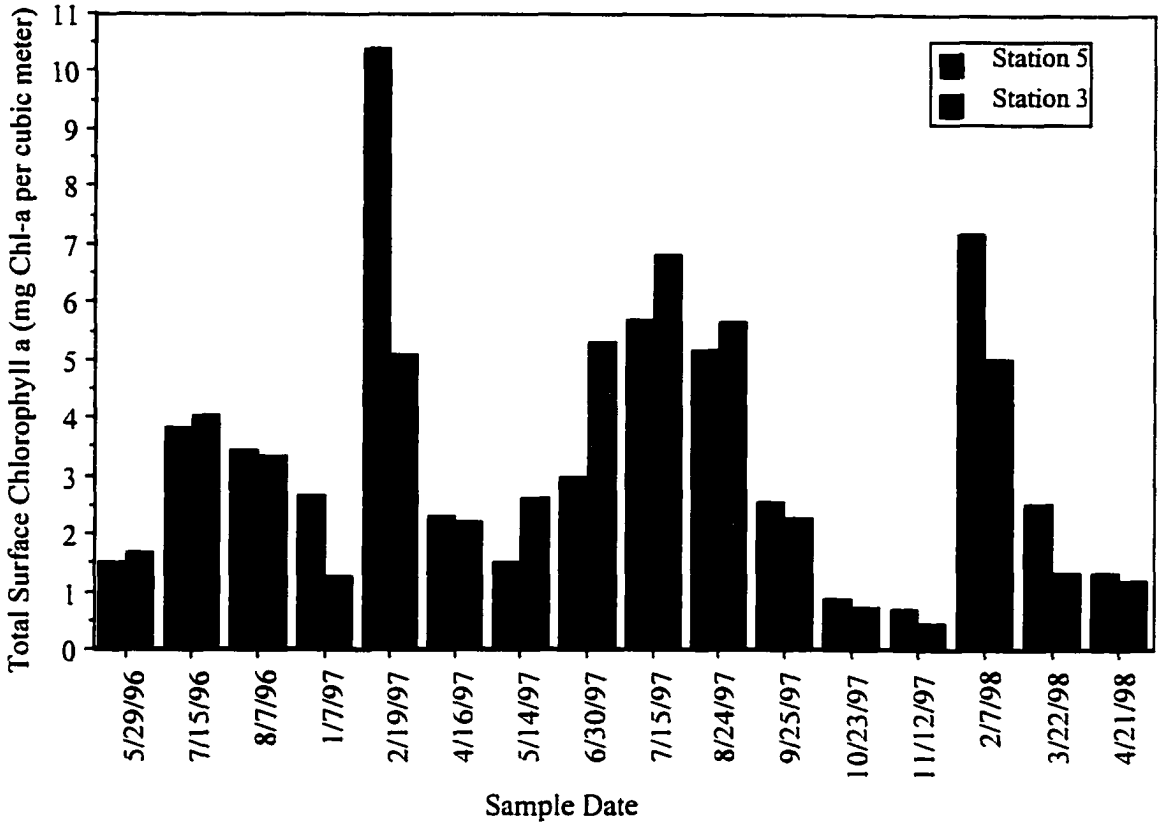

Fig. 27. Total surface chlorophyll *a* concentrations (mg Chl-*a* m^{-3}) measured at station 5 and 3 along the Greens Creek transect for sampling dates May 29, 1996 through April 21, 1998.

Yearly phytoplankton production estimates were calculated by integrating the measured daily production values determined for each station over an annual cycle. Model derived annual productivity was estimated to be 62.54 g C m^{-2} $year^{-1}$ and 37.14 g C m^{-2} $year^{-1}$ for station 5 and 3 respectively. However, the annual results based on the daily-derived productivity values varied significantly with values ranging from as low as

8.64 g C m^{-2} $year^{-1}$ to 222.49 g C m^{-2} $year^{-1}$ at station 5 and as low as 3.17 g C m^{-2} $year^{-1}$ to 134.42 g C m^{-2} $year^{-1}$ at station 3. Given the wide range of conditions over an annual cycle, mean phytoplankton productivity estimates determined by this model are comparably less than productivity estimates determined by using experimental C^{14} techniques. Under ideal culture conditions, phytoplankton productivity has been estimated on several occasions for Greens Creek with results ranging from 110 – 170 g C m^{-2} $year^{-1}$. This is nearly a two-fold increase over model derived production estimates.

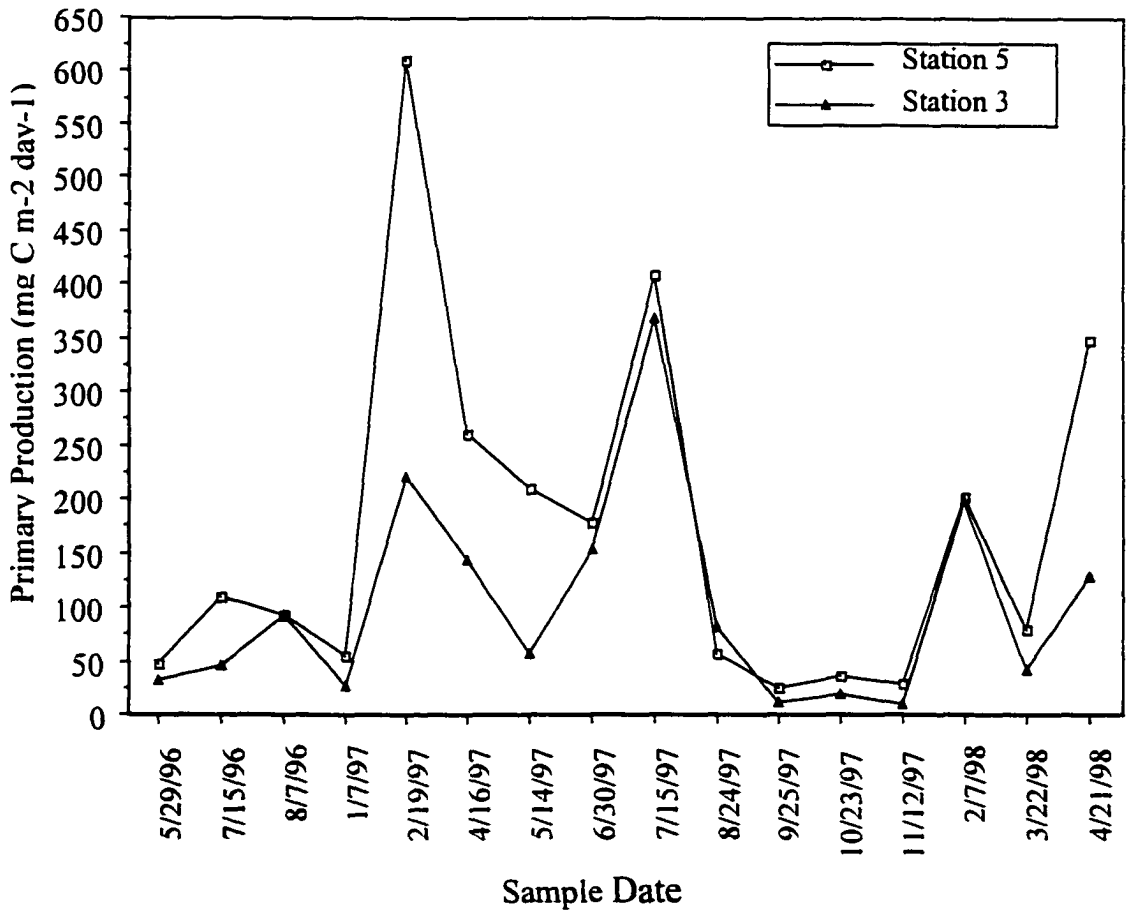

Fig. 28. Seasonal variations of total primary production estimations (mg C m^{-2} day^{-1}) for station 5 and 3 throughout the sampling period (May 29, 1996 - April 21, 1998).

The principal problem encountered with both the model and mesocosm experiments is typically having to interpolate daily (or 24 hour) production based on instantaneous surface irradiance measurements or incubations which last only several hours. There is also an added difficulty in interpolating annual production from daily estimates. The model data presented here not only suggests annual production values are highly variable due to variations in light but also to daily variations in biomass and photic depths compounded on an annual cycle. These results also show the danger in estimating annual productivity from single locations within an estuary since phyotplankton productivity can vary significantly along even small spatial gradients.

Zooplankton Analysis

In order to evaluate changes in phytoplankton production it is important to investigate changes in the associated zooplankton community. Oblique plankton tows were taken at station 3 in Greens Creek from September 1997 through May 1998. Zooplankton density expressed as number per liter showed large temporal variations among tows, although a seasonal pattern is apparent (Fig. 29). These results show the development of two blooms throughout the sampling period with maximum biomass occurring first during the late fall (November 1997) and again during the spring months. Of the two bloom events biomass estimates were greater during the summer months (March – May) with maximum densities occurring in March 1998. On average, zooplankton biomass was measured to be less than 2000 animals per liter for the collected samples with densities showing large temporal variability ranging from as low as 16.40 animals/L to as high as 10,789.76 animals/L. The overall population densities for each tow varied greatly over the study period. The maximum measured biomass was recorded to be 10,789.76 number/L on March 22, 1998 with the minimum biomass of 16.40 animals/L measured on September 22, 1997.

Zooplankton species composition changed little from season to season throughout the sampling period. All tow samples throughout this research were dominated by two copepod genera, *Acartia* and *Centropages*. Other zooplankton species were found in low numbers including fish larvae, jellyfish, juvenile welch and horseshoe crabs. Final

results show that the fall (November 1997) bloom has less biomass than the spring (March 1998) bloom with densities equivalent to 950.97 animals per liter and 10,789.76 animals per liter respectively, although the fall bloom had greater species diversity than the spring bloom.

Phytoplankton cell density as compared to zooplankton cell density are shown in Figure 30 in order to investigate the relationship between phytoplankton biomass and the corresponding grazing pressure by zooplankton. The results of this research indicate that there is very little grazing pressure exerted by the zooplankton population on the associated phytoplankton population. Grazing by zooplankton only accounts for approximately 2% of the phytoplankton mortality within the system. Therefore, the consideration of a single parameter in controlling phytoplankton abundance is often not satisfactory.

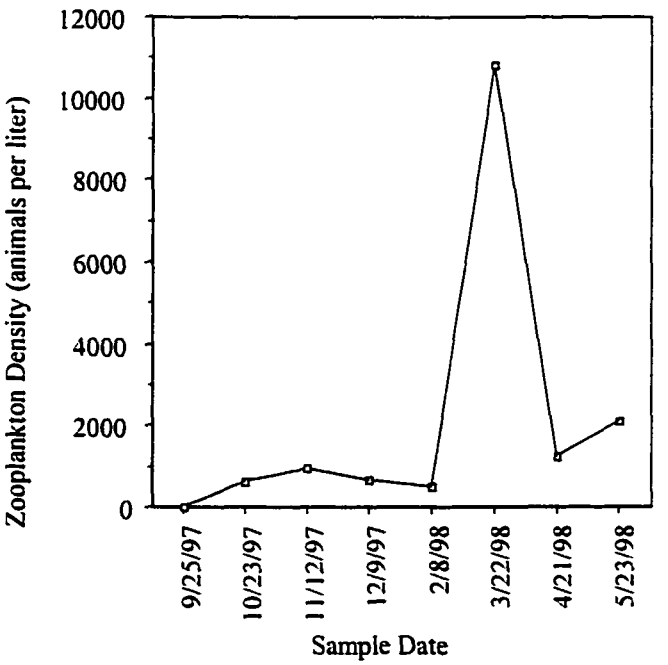

Fig. 29. Zooplankton densities of Greens Creek at station 3 over the sampling period (September 1997 through May 1998).

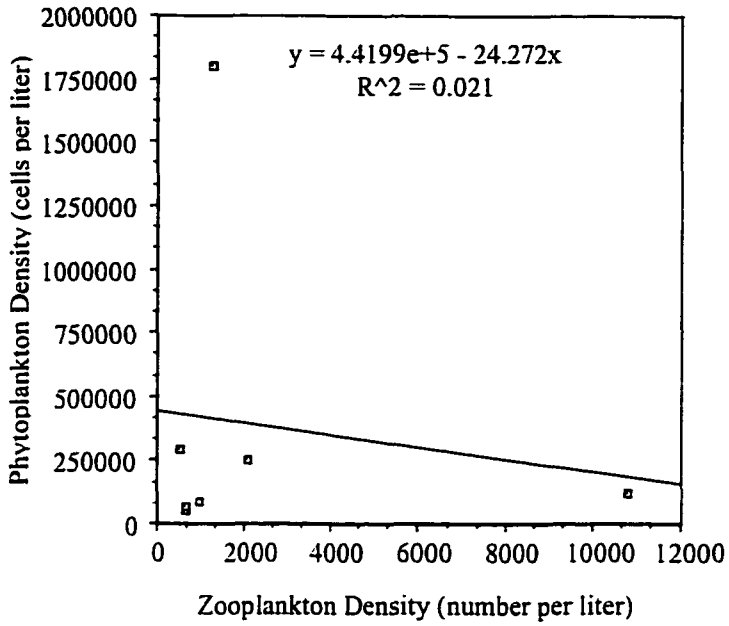

Fig. 30. Zooplankton density as compared to phytoplankton densities for all collected plankton tows and corresponding phytoplankton cell enumeration determinations.

Physical Parameters

Physical parameters were investigated in Greens Creek to determine the effects of tidal flushing on the response of phytoplankton populations to varying nutrient inputs. Tidal range and associated processes such as tidal mixing and current velocity can greatly influence phytoplankton biomass within a system. Greens Creek has a typical tidal range of approximately 1.4 meters and is characterized as a microtidal system in which the tidal range is less than two meters. At high tide, Greens Creek inundates the surrounding *Spartina alterniflora* marsh characterized by the long form at the creek margins and the short form that occupies the higher levels of the marsh near the upper limit of the tidal influence. In contrast at low tide, the marsh is completely exposed with water depths generally decreasing several feet below the creek levee.

Current speed and corresponding direction measurements were obtained over a 30-hour cycle (October 22 – 23, 1996) using an Acoustic Doppler Current Profiler (ADCP) at station 4 near the mouth of Greens Creek. The ADCP was deployed at peak

low tide on October 22, 1996 and retrieved on the third hour of recharge on October 23, 1996 thereby encompassing two complete tidal cycles. Current velocities over the 30-hour cycle ranged from as low as 0.6 cm/s to as high as 79.0 cm s^{-1} (Fig. 31). Maximum velocities were greater during the flood than the ebb cycles with speeds reaching up to 79.0 cm s^{-1} during the fourth and fifth hours of recharge. Ebb cycle velocities were slightly lower (70.4 cm s^{-1}) with maximum speeds occurring during second and third hours of discharge. Even though the maximum velocities were achieved during recharge events, mean current velocities were greater during the ebb flow than the flood flow with mean velocities equivalent to 36.5 and 27.0 cm s^{-1} respectively. These results show that the flood at the entrance of Greens Creek is much more asymmetrical while the ebb is only slightly asymmetrical.

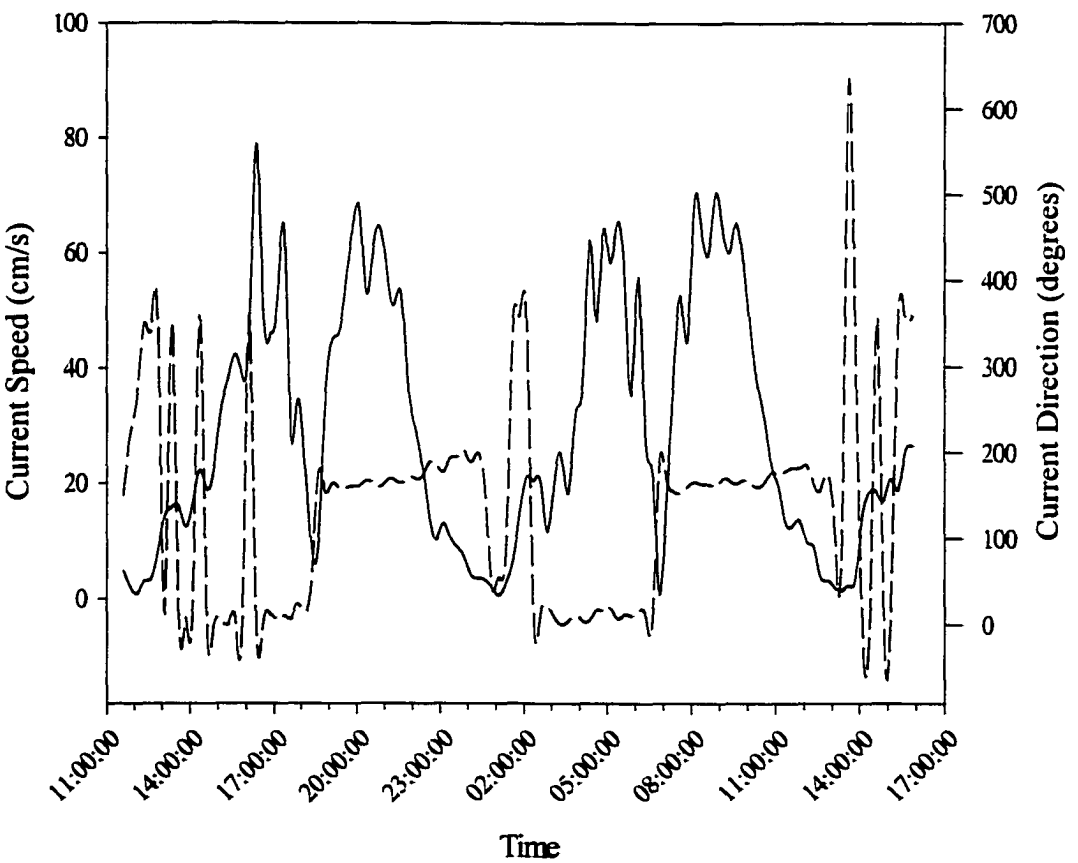

Fig. 31. Current speed and direction measurements over a 30-hour time period (October 22 –23, 1996). Solid line represents current speed and dashed line represents current direction.

In addition to current speed and direction, salinity measurements were also obtained over the 30-hour tidal study with the ADCP. Tidal exchange also produced fluctuations in the observed salinity at station 4. Figure 32 shows the variations in salinity with values ranging from 24.628 during low tide conditions to as high as 28.501 directly following peak recharge. Flood tides bring in higher salinity water to the creek with ebb tides allowing the freshwater signal to be most evident. For this reason, all water column stations along the transect were sampled during peak ebb conditions. High verses low tide's nutrient and chlorophyll profiles were investigated on several sampling occasions and showed a 50% dilution of both nutrient and chlorophyll *a* concentrations between high and low tides. These profiles provide adequate evidence that at certain times of the year Greens Creek supplies a substantial contribution of nutrients and production to the adjacent Machipongo River and Hog Island Bay.

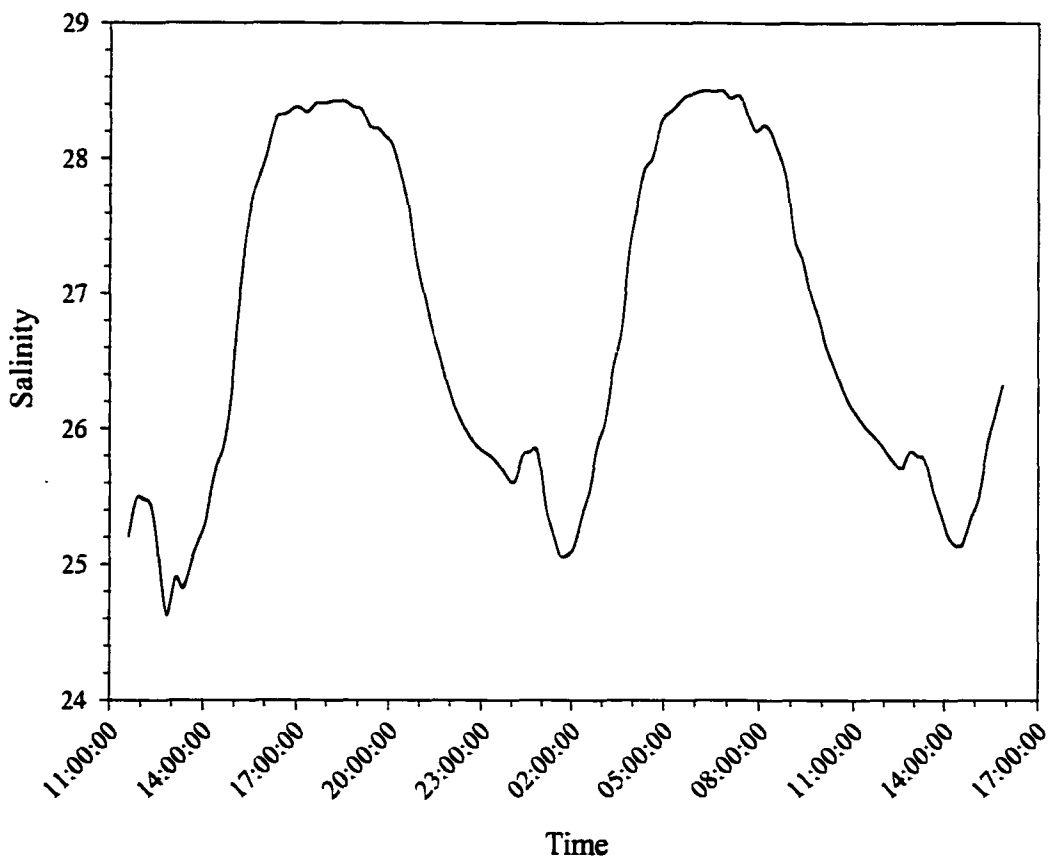

Fig. 32. Salinity fluctuations at station 4 over the 30-hour ADCP tidal study (October 22 - 23, 1996).

The determination of additional tidal parameters such as hydraulic turnover time (HTT) and estuary number (e) also provide valuable insight into the behavior of upland nutrients as they are transported through the Greens Creek system. Hydraulic turn-over time (HTT), defined as the time it takes to exchange all of the water in a basin under the assumption that there is complete mixing, was determined for Greens Creek. Based on the previously mentioned 30-hour current velocity measurements and a basin capacity of Greens Creek approximating 0.949 ($*10^6$) m^3, the HTT of the Greens Creek basin was estimated to be 7.1 hours. In addition to the hydraulic turnover time of Greens Creek, the estuary number (e) that describes the potential flow characteristics of streamlines associated with creek was also determined. In essence, the estuary number describes the nature of the water as it passes through the inlet. An estuary number equal to 0.029 was calculated and describes the creek water ebbing toward the inlet as having stratified flow conditions typical of a plume. In general, the continuous influx of freshwater from the reservoir spillway with an average discharge rate equal to 3.39 $m^3 s^{-1}$ is continually trying to stratify the water column. Inversely, well-mixed saline water is trying to mix the water column and break down the salt-water wedge due to the increased tidal energy associated with the incoming tides.

Greens Creek Water Quality

Now that the primary sources of nutrient loading have been discussed for the Greens Creek watershed it is important to focus on the impacts that these nutrient sources have on the primary production occurring within the system. The continuous flux of freshwater discharge (i.e. groundwater and reservoir discharge) and additional direct and indirect inputs by episodic rainfall events into the creek bring with it nutrients (N, P, and Si) available for phytoplankton uptake. In order to investigate the potential relationship between nutrient loading and phytoplankton uptake, one must first determine how the observed nutrient distributions in the creek are affected by the dynamic salinity conditions. In addition, the extent to which nutrients are exported to the nearby coastal lagoon depends to a large degree on how the quantity and nature of the nutrients are modified within the creek system.

Regression equations (Fig. 33a-d) were determined for nitrate, phosphate, silicate and total chlorophyll *a* concentrations as compared to salinity in order to investigate the nutrient behavior of freshwater discharge as it travels through Greens Creek where it is available for phytoplankton uptake. There are no strong correlations between any of the measured parameters and salinity. Nitrate concentrations (Fig. 33a) exhibited the strongest correlation ($r^2 = 0.351$) with the ambient salinity as compared to the other measured parameters such as PO_4^{3-}, SiO_2 and total chl-*a*, although it is a very weak relationship. Similar to the regression equation determined for NO_3^-, the regression value equated for phosphate concentrations (Fig. 33b) also shows a marginal correlation with salinity ($r^2 = 0.184$). This data suggests that biogeochemical processes control the observed nutrient concentrations rather than physical mixing processes.

Conversely, the regression values equated for both silicate (Fig. 33c) and total chlorophyll *a* (Fig. 33d) show no apparent relationship with salinity. Regression values were equated to be $r^2 = 0.003$ and $r^2 = 0.006$ for silicate and total chl-*a* respectively providing evidence that local processes within the water column dominantly control the available nutrient concentrations of both of these parameters. Overall, these results validate the premise that local processes other than physical mixing of nutrient-rich freshwater and nutrient-limited seawater are responsible for the observed distributions of NO_3^-, PO_4^{3-}, SiO_2 and total chl-*a* within Greens Creek.

Marine systems are typically N-limited therefore the bioavailability of nitrogen within this system is extremely important for phytoplankton production. Overall, all measured N fractions showed large temporal and spatial fluctuations over the sampling period with NO_3^- concentrations representing the greatest total concentration of N (Table 20). However, NO_3^- also showed the greatest variation in concentrations compared to both NH_4^+ and NO_2^-. Maximum N concentrations were measured to be 706.21 μM, 8.97 μM and 2.2 μM for NO_3^-, NH_4^+ and NO_2^- respectively. Ammonium and nitrate concentrations were the most significant form of nitrogen with mean compositions equivalent to 22% and 78% respectively. Nitrite concentrations were consistently the most negligible N species accounting for a mean composition of 5% with concentrations ranging from below detection limits to ~ 2.2 μM for all sampling events.

TABLE 20. Concentration ranges and percent compositions of nitrate, ammonium and nitrite species measured over the sampling period.

N-species	Ranges		Mean Percent Composition
	Concentration (μM)	Percent Composition (%)	
NO_3^-	~1 – 706	20 – 99	78
NH_4^+	0.2 - 9	1 - 66	22
NO_2^-	0 – 2.2	0 - 34	5

For this section of research the water quality data was interpreted using property-property plots. These nutrient profiles serve as an aid to better understand the behavior of freshwater borne nutrients within the marine water-column as well as those processes that regulate the input, removal and recycling of these nutrients within Greens Creek. By examining such plots, two mixing patterns become apparent: linear (conservative) or non-linear (non-conservative). The extent to which the processes within the system effect the behavior of nutrients is determined by nutrient-salinity relationships that are controlled by the mixing of nutrient-rich freshwater and nutrient-poor saltwater. Conservative behavior, or linear mixing, of nutrients and salinity measurements along a transect emphasizes the small influence that local processes have on controlling nutrient concentrations within that system. Conversely, when local biogeochemical processes strongly influence the observed nutrient fluctuations within a system, non-conservative behavior is observed.

To determine the significance of nutrient concentrations available for phytoplankton uptake and gain valuable insight regarding Greens Creek as an exporter of nutrients and production to the adjacent coastal lagoon, nutrient profiles were created for all sampling dates during this research (Fig. 34 - 46). Recall that all water column

sampling took place during ebb flow when freshwater discharge is greatest and the freshwater signal is most evident. Overall, the distribution of all measured nutrient species showed concentration fluctuations along the Greens Creek transect on all sampling dates. The details of the NO_3^-, NH_4^+, PO_4^{3-} and SiO_2 nutrient profiles show that over an annual cycle, there are generally only two apparent patterns of distribution for each measured nutrient. Nitrite profiles over the research period are not shown since changes in concentrations are so small over the spatial extent of the transect and among individual sampling dates.

As a whole, nitrate concentrations for all sampling dates (Fig. 34 - 46) show slight to moderate removal in the lower reaches of the transect (stations 3 through 5) with some nitrate addition in the upper to mid-reaches (reservoir spillway to station 3A) on several of the sampling dates. Nitrate addition curves are evident on August 24, 1997 (Fig. 39), October 23, 1997 (Fig. 41), February 7, 1998 (Fig. 44), March 22, 1998 (Fig. 45) and April 21, 1998 (Fig. 46) in the lower salinity waters of the creek with removal occurring in the more salinity waters. Nitrate concentrations at the reservoir spillway range from roughly 60 μM to as high as 706 μM. In all instances, NO_3^- concentrations decrease non-linearly as salinity increases; thereby providing evidence that local biogeochemical processes are strongly influencing nutrient concentrations along the transect. In the lower reaches of the transect, NO_3^- nutrient concentrations are significantly lower than those measured in the upper reaches with concentrations decreasing to less than 10 μM. These profiles provide evidence that a large percentage (~90 – 98%) of the total nitrate imported to the creek via freshwater sources is removed due to local processes.

Similar to the nitrate profiles, ammonium concentrations tend to show NH_4^+ production in the upper to mid-reaches of the transect (reservoir spillway to station 3B) with consumption occurring in the lower more saline reaches (stations 3 – 5). There are some exceptions to this trend in which NH_4^+ concentrations increased along the entire length of the transect. Sampling dates in which only production occurred include August 24, 1997 (Fig. 39), October 23, 1997 (Fig. 41) and December 9, 1997 (Fig. 43). Ammonium concentrations are significantly smaller than those previously described for nitrate with values ranging from 0.2 to 7.7 μM over the sampling period.

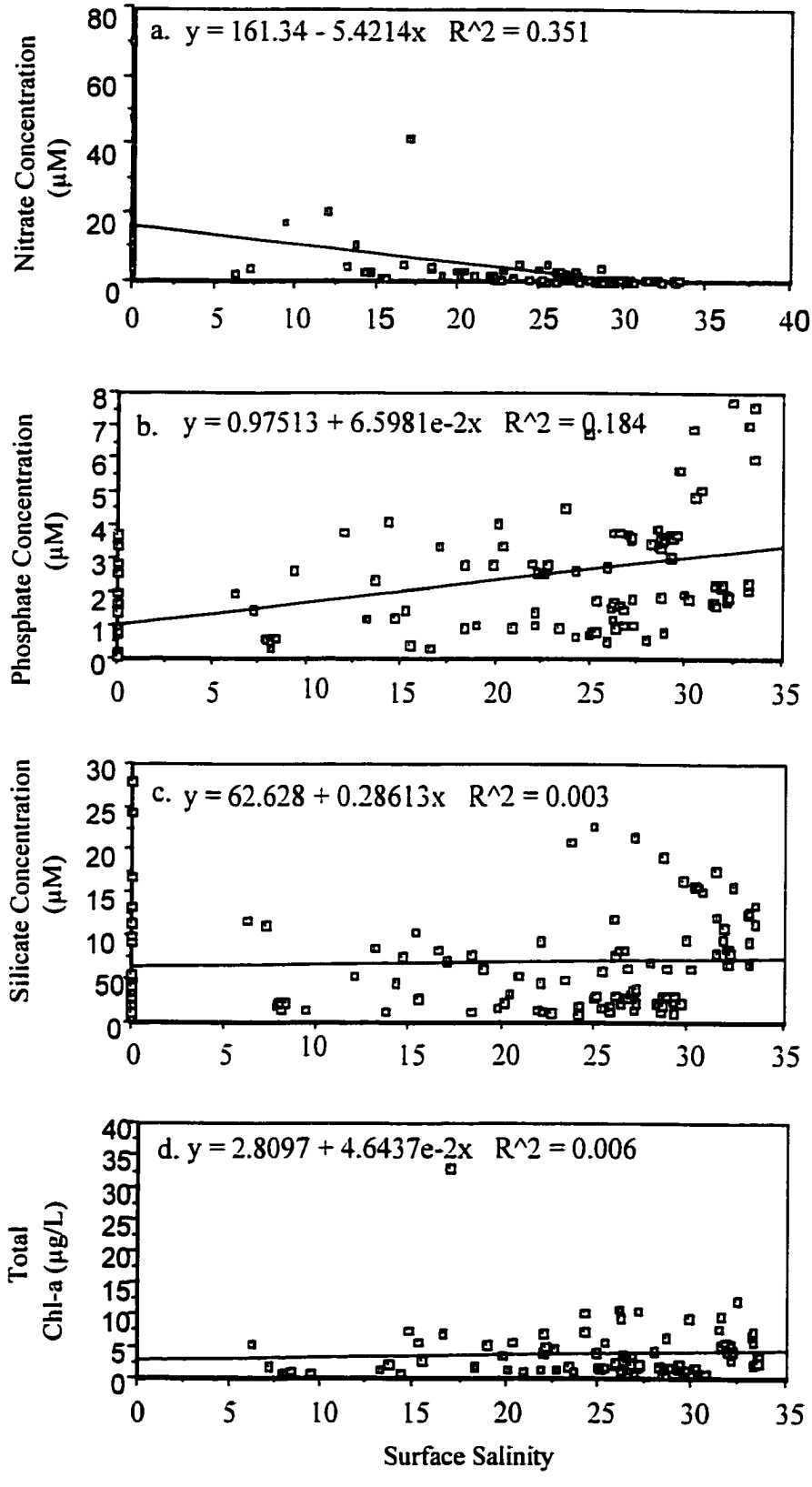

Fig. 33. Linear regression equation to determine the relationships between a.) NO_3^-, b.) PO_4^{3-}, c.) SiO_2 and d.) total chlorophyll *a* (µg/L) and salinity.

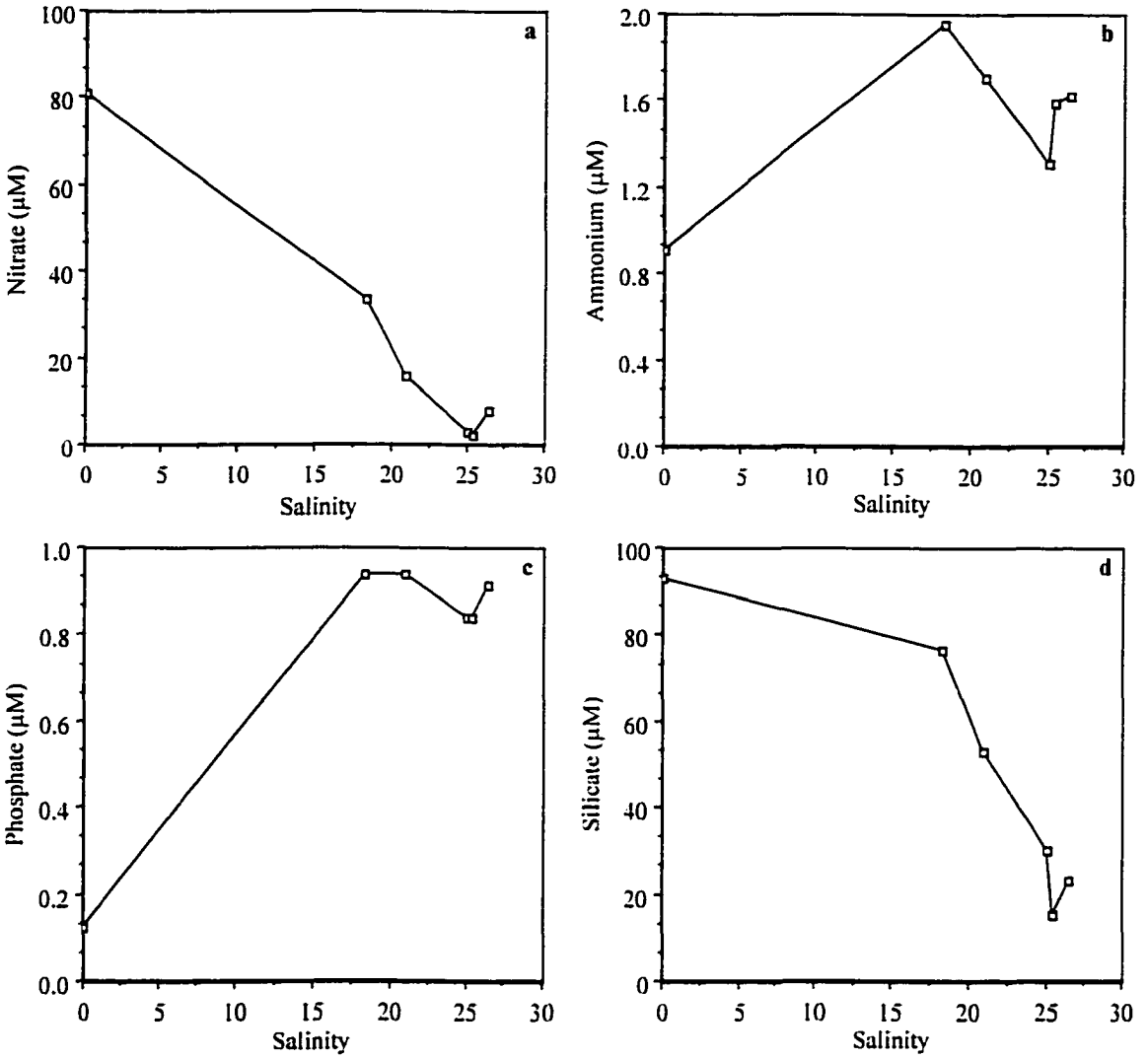

Fig. 34. January 7, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

In general, the non-conservative NH_4^+ behavior indicates either an external input of ammonium along the transect (i.e. sub-surface shallow groundwater) or the reduction of NO_3^- to NH_4^+ due to denitrification processes at work in the water-column. It is unlikely that denitrification processes in the water-column are controlling ammonium production since there is an abundance of dissolved oxygen in this high-energy tidal creek. These profiles render confirmation that there is a significant contribution (~1 µM) of additional ammonium supplied to the upper reaches of the Greens Creek water column

throughout most of the year. In addition, NH_4^+ is being consumed speculatively by biological processes in the lower reaches of the transect.

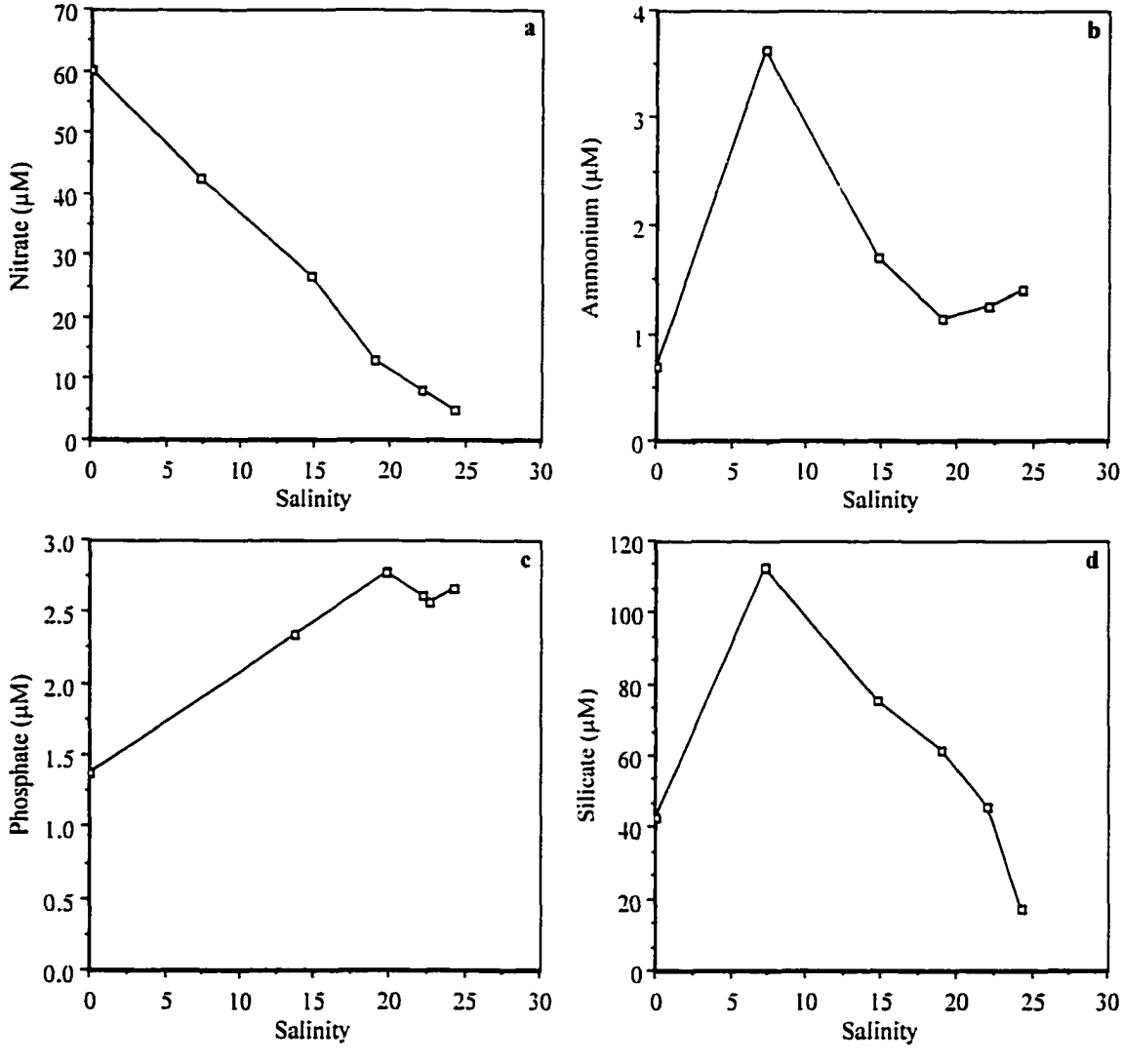

Fig. 35. February 19, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

In addition to N, dissolved reactive phosphate is also vital for phytoplankton growth and production. Unlike the results described for nitrate and ammonium,

phosphate profiles show discernible input occurring along the entire length of the transect with concentrations increasing with salinity from the reservoir spillway to station 5. The pattern of PO_4^{3-} production along the transect is altered in the mid- to late summer months in which slight P-removal occurs in the upper to mid- reaches of Greens Creek with observed inputs occurring in the lower saline reaches of the transect.

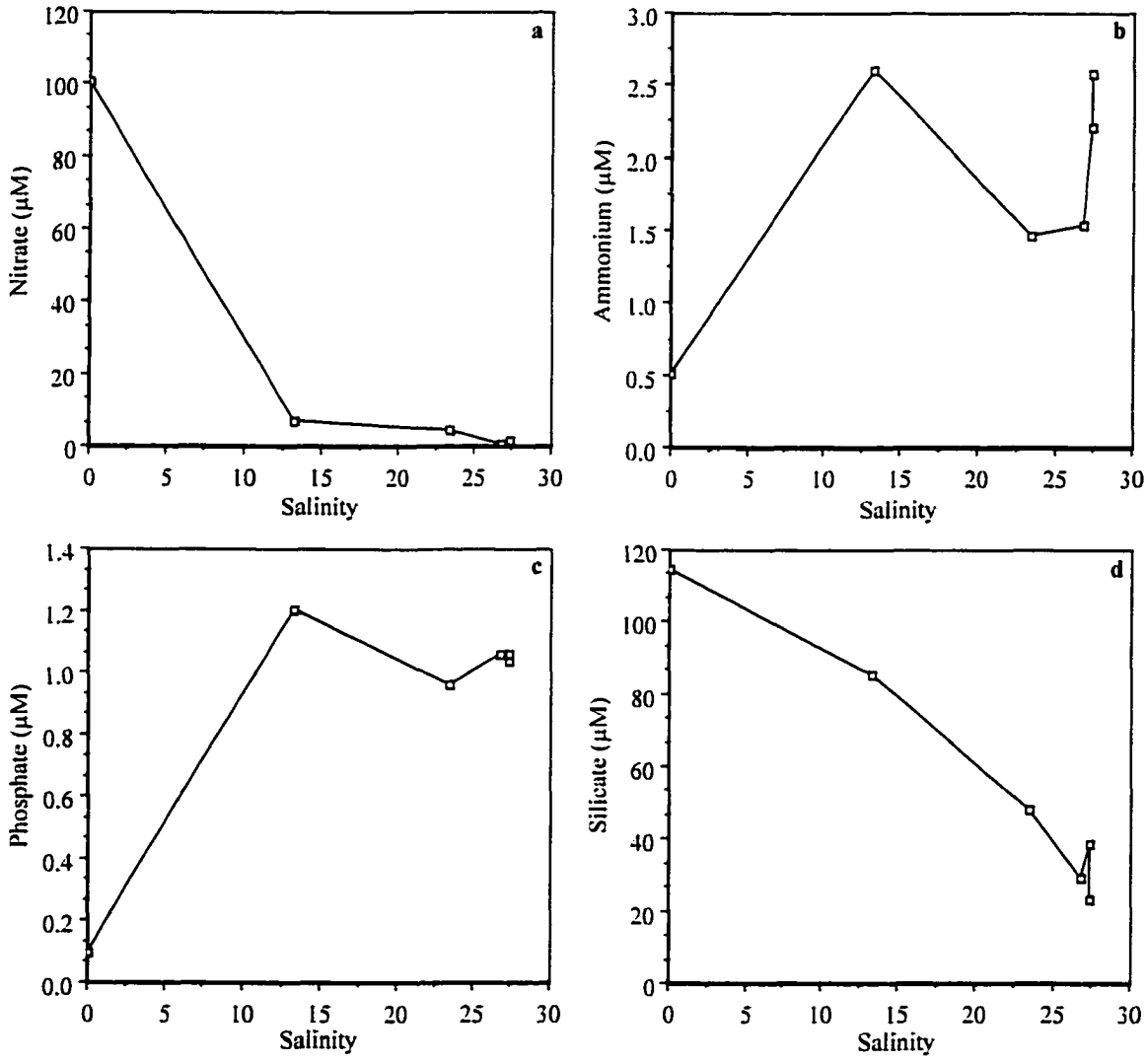

Fig. 36. April 16, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

This trend is clear on June through August 1997 sampling dates (Fig. 37 – 39) and October 1997 (Fig. 41). In addition to these two phosphate trends, a third pattern is visible. On January 7, 1997 (Fig. 34) and September 25, 1997 (Fig. 40), phosphate is added to the creek water column from the reservoir spillway to station 3A with removal occurring from station 3A to the end of the transect at station 5.

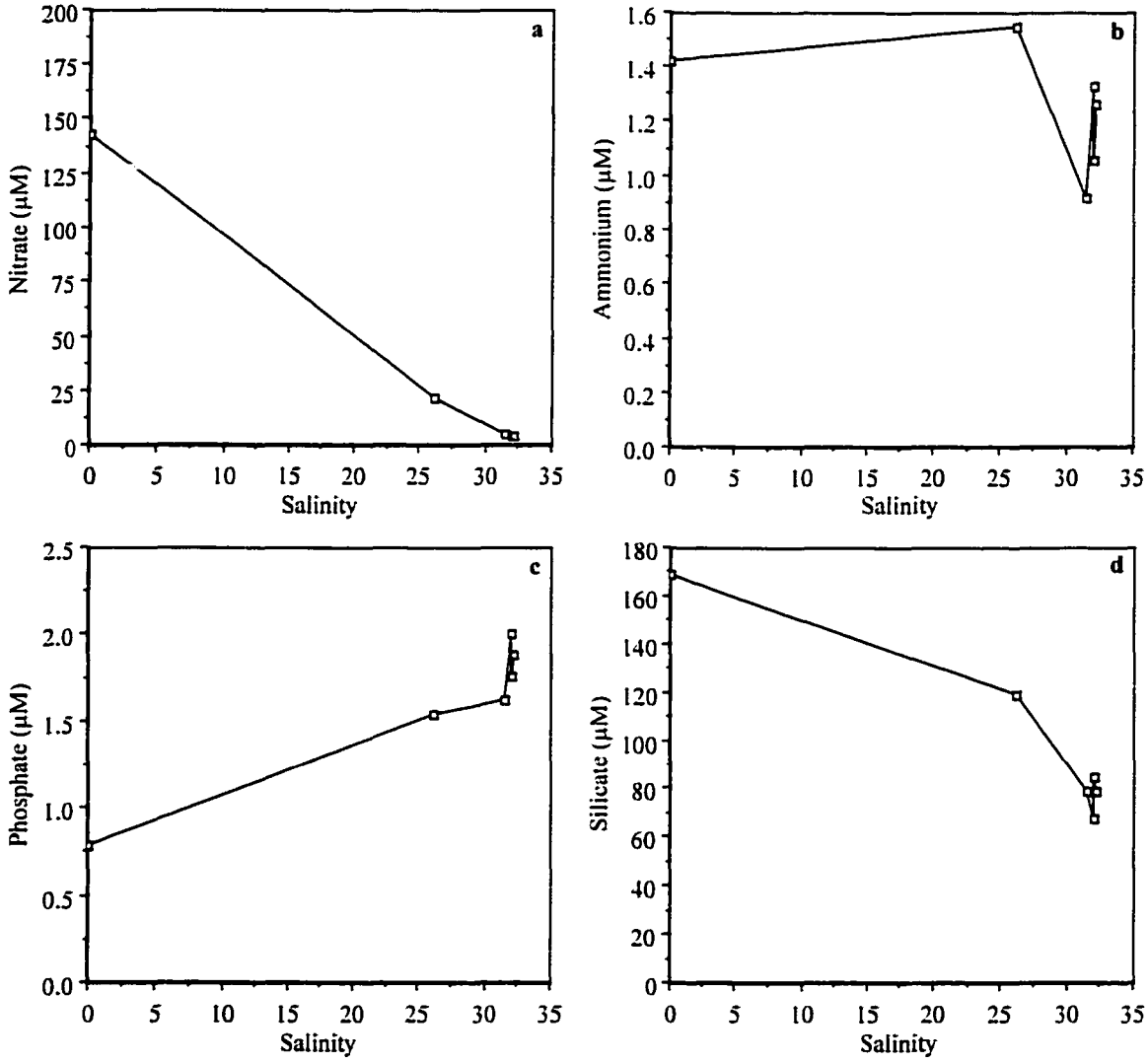

Fig. 37. June 30, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

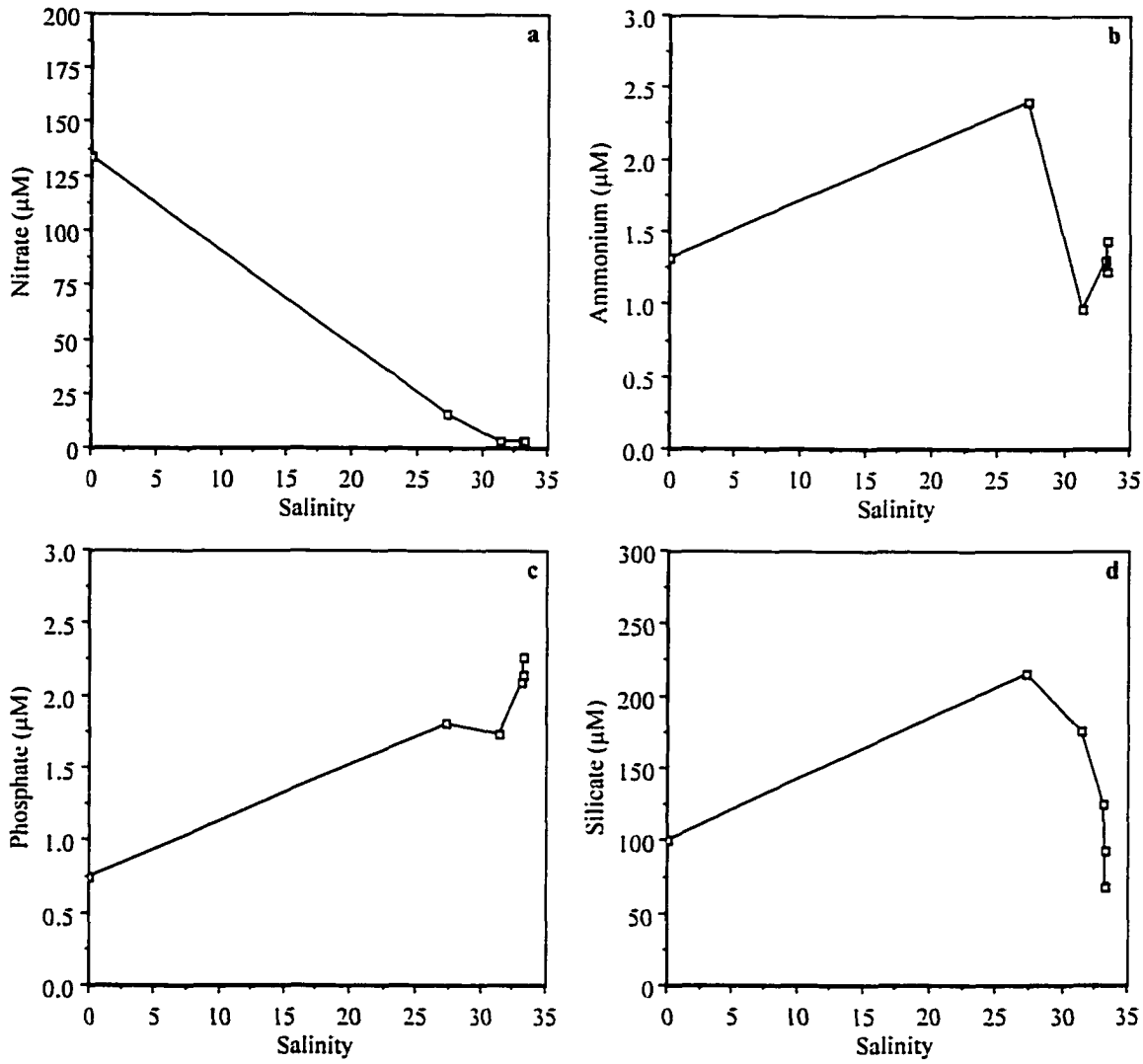

Fig. 38. July 15, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

Concentrations of PO_4^{3-} display great temporal and spatial variability on all sampling dates but concentrations generally ranged between 0 – 8 µM. However, concentrations did go as high as ~16 µM in the mid-reaches of the creek on February 7, 1998 (Fig. 44). Over the sampling period, dissolved reactive phosphate exhibits non-linear, or non-conservative, behavior with freshwater concentrations being less than those concentrations measured in the more saline waters of the transect.

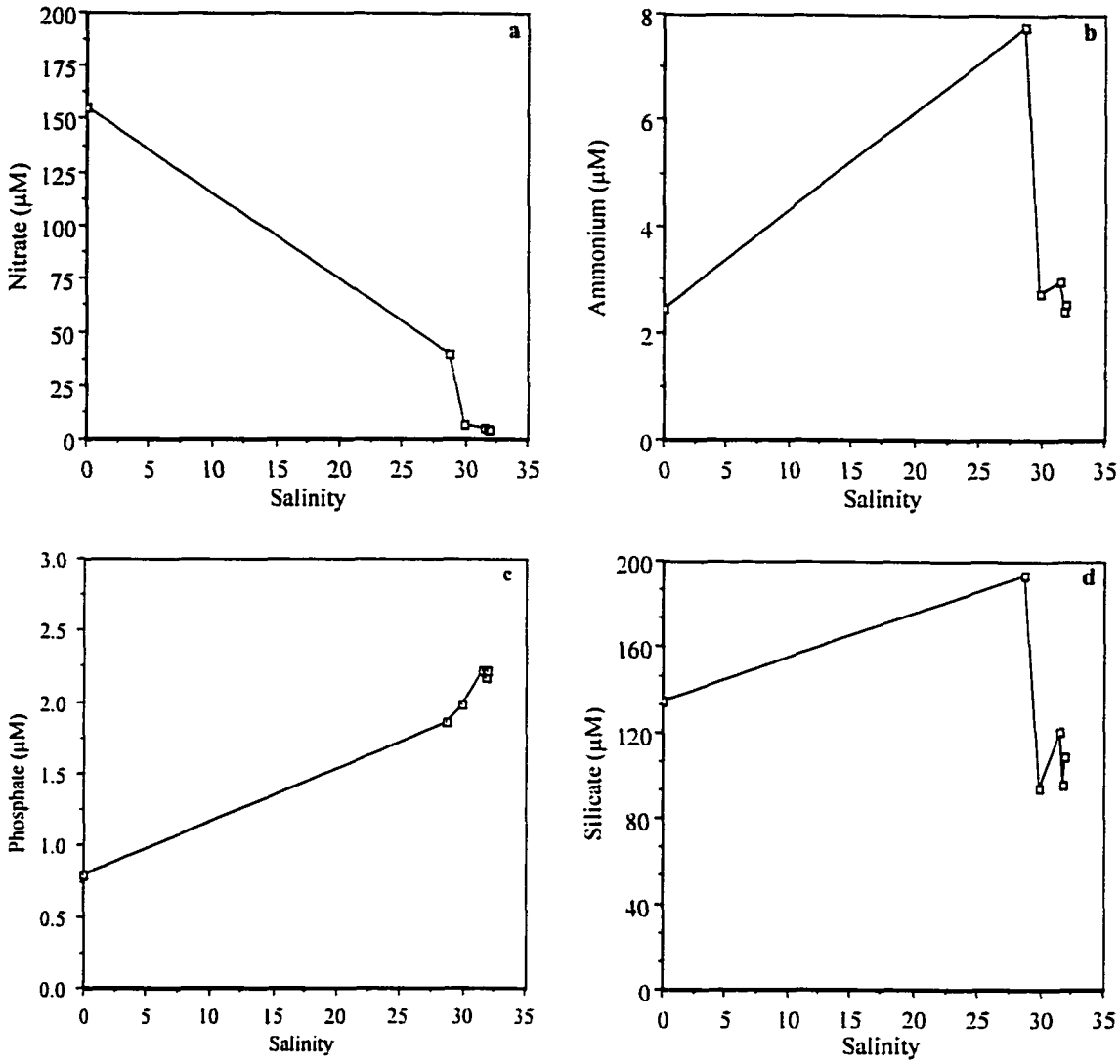

Fig. 39. August 24, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

The non-conservative behavior provides evidence of PO_4^{3-} being released from riverine particulate matter rather than the mixing of P-limited freshwater and P-rich marine water.

Dissolved silica is the most simple and most effective tracer of the reactive effects of freshwater flow and phytoplankton productivity especially in areas where diatoms are a large component of the population. Silicate concentrations show prominent signs of

input throughout the course of the study with intermittent periods of removal occurring only in the lower reaches (stations 3 – 5) of the transect.

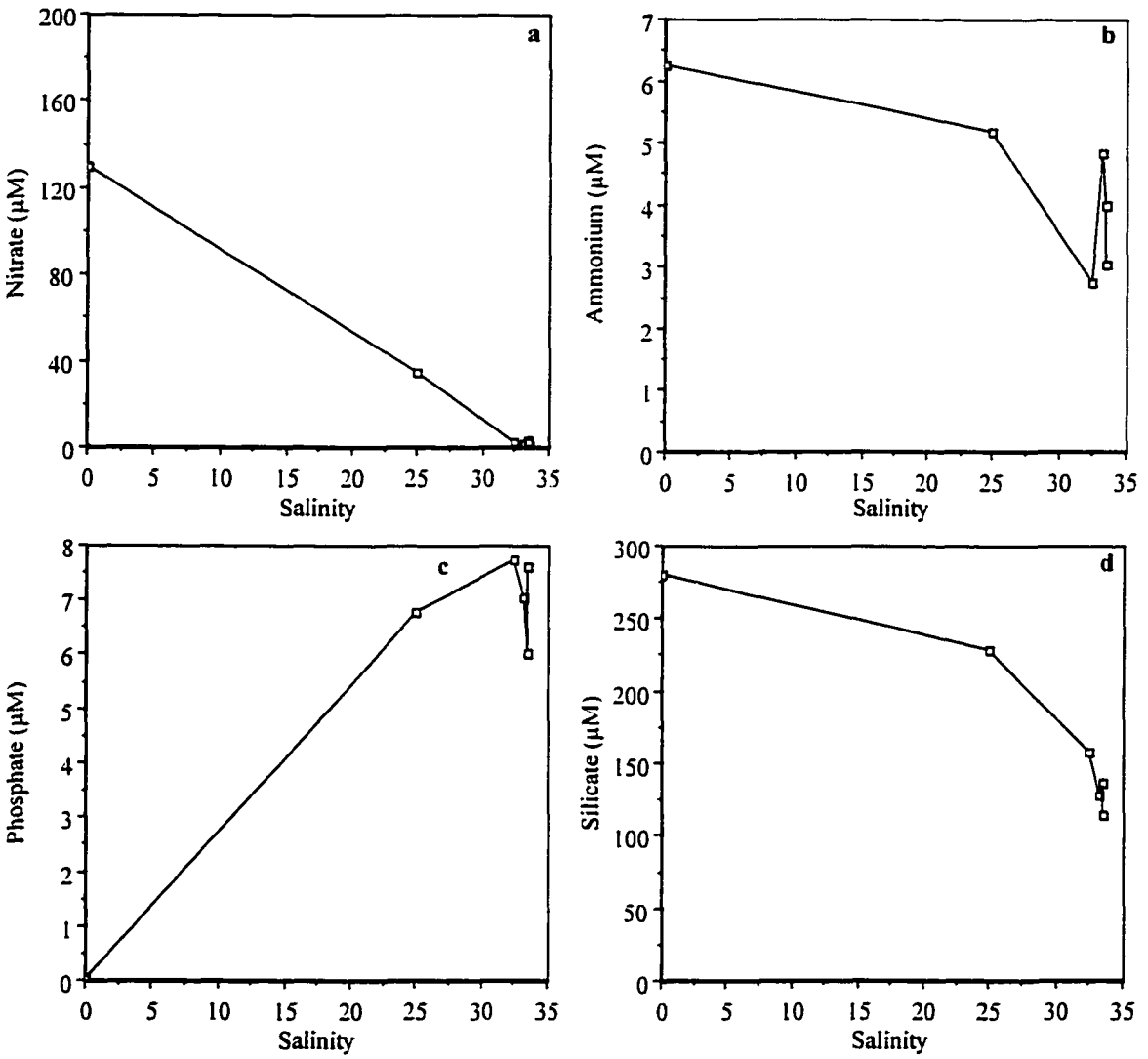

Fig. 40. September 25, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

The pattern of non-linear behavior provides evidence that local processes such as phytoplankton uptake and geochemical dissolution control the concentrations of available

silicate in the water column of Greens Creek. It is difficult to decipher any seasonal trend in silicate uptake over the annual cycle. Although silicate removal was evident in the lower reaches of the water column transect on January 7, 1997 (Fig. 34), June 30, 1997 (Fig. 37), August 24, 1997 (Fig. 39), November 12, 1997 (Fig. 42) and March 22, 1998 (Fig. 45).

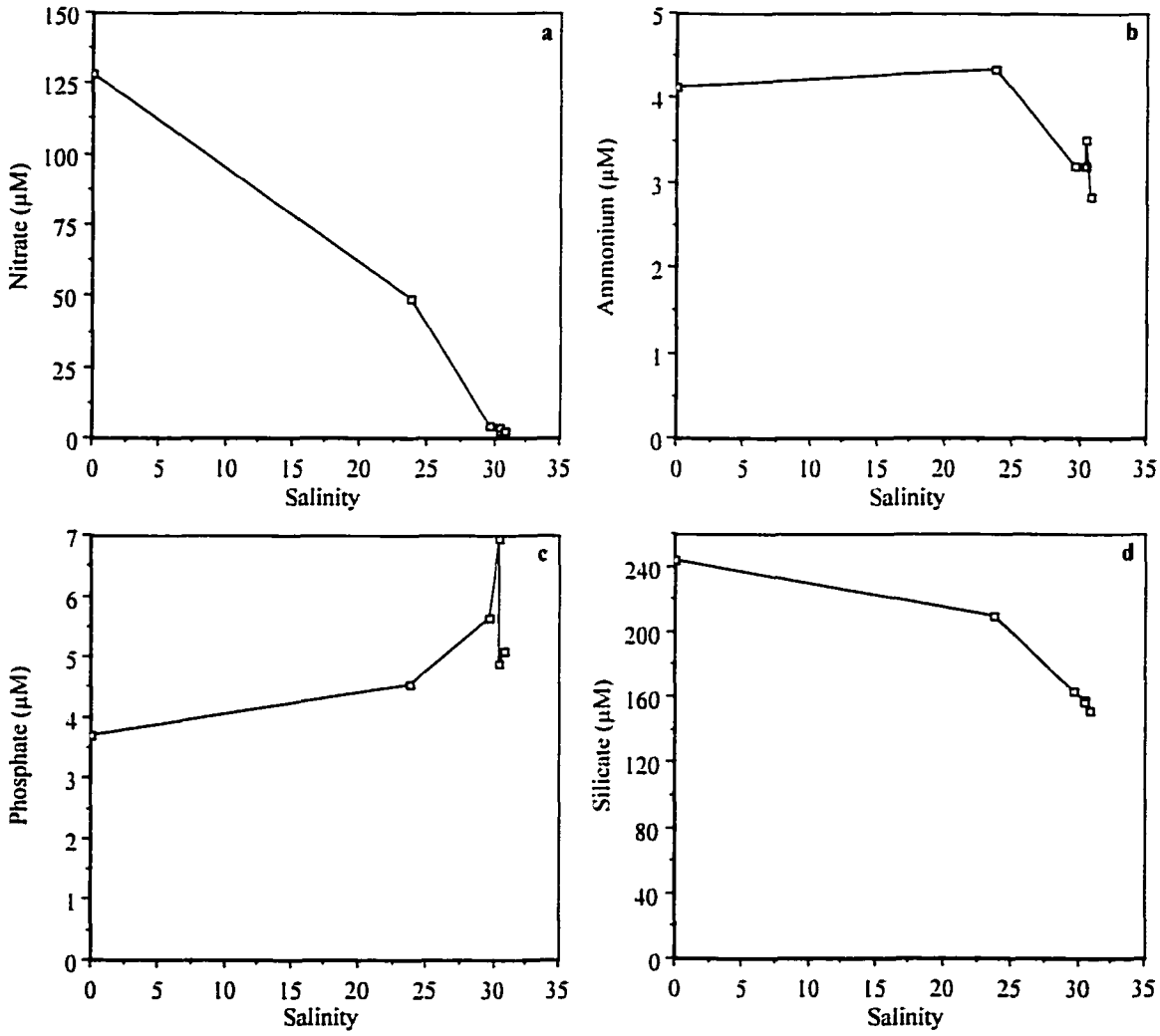

Fig. 41. October 23, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

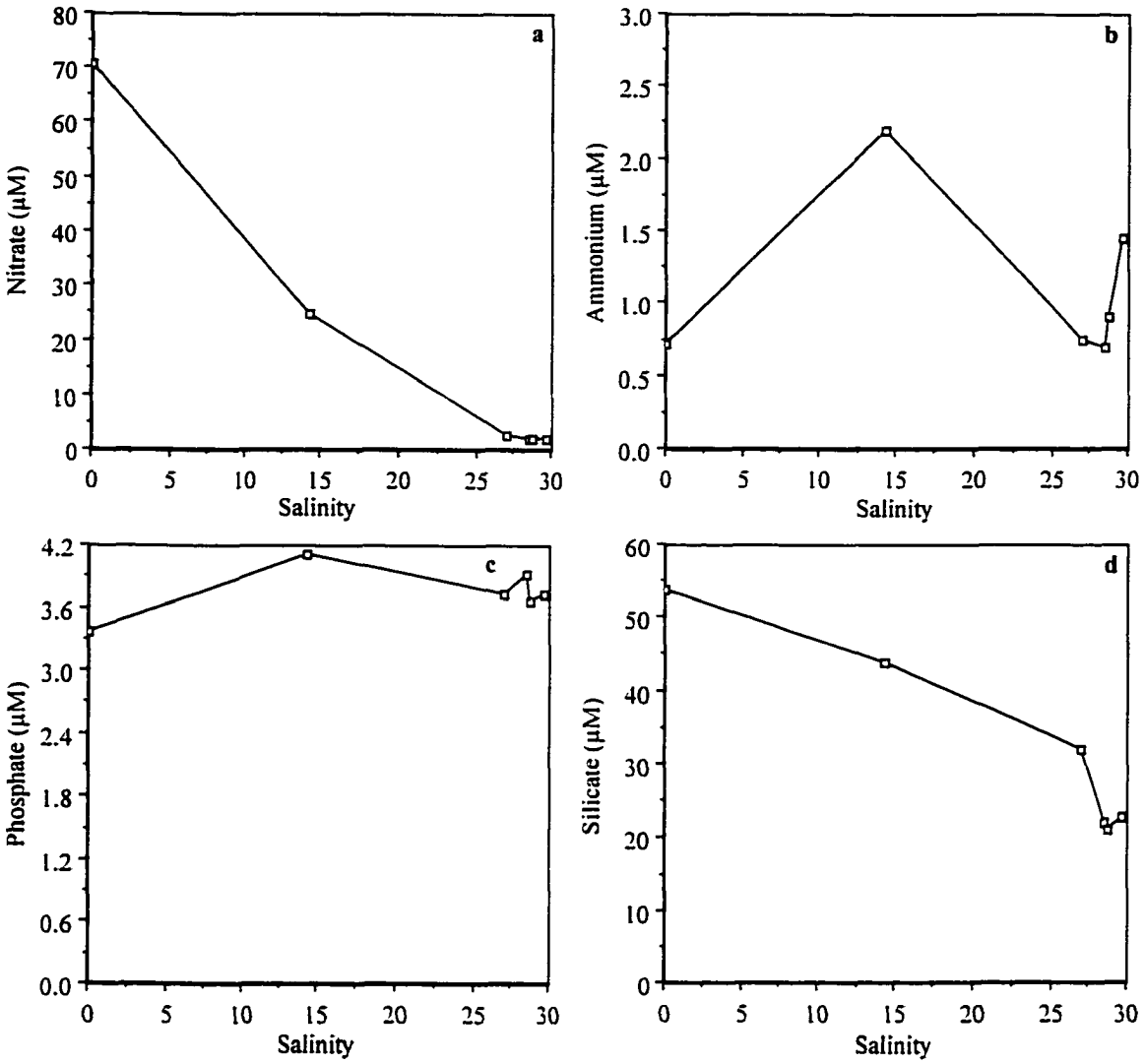

Fig. 42. November 12, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

Maximum [SiO_2] were measured at the reservoir spillway as high as ~275 µM with concentrations decreasing to as low as ~6 µM at station 5.

Overall, nutrient profiles for NO_3^-, NH_4^+, PO_4^{3-} and SiO_2 exhibit non-linear behavior concluding that measured concentrations are controlled by local processes occurring within the system. The continuous flux of freshwater discharge available for

phytoplankton uptake is affected by more than the dynamic salinity conditions within Greens Creek.

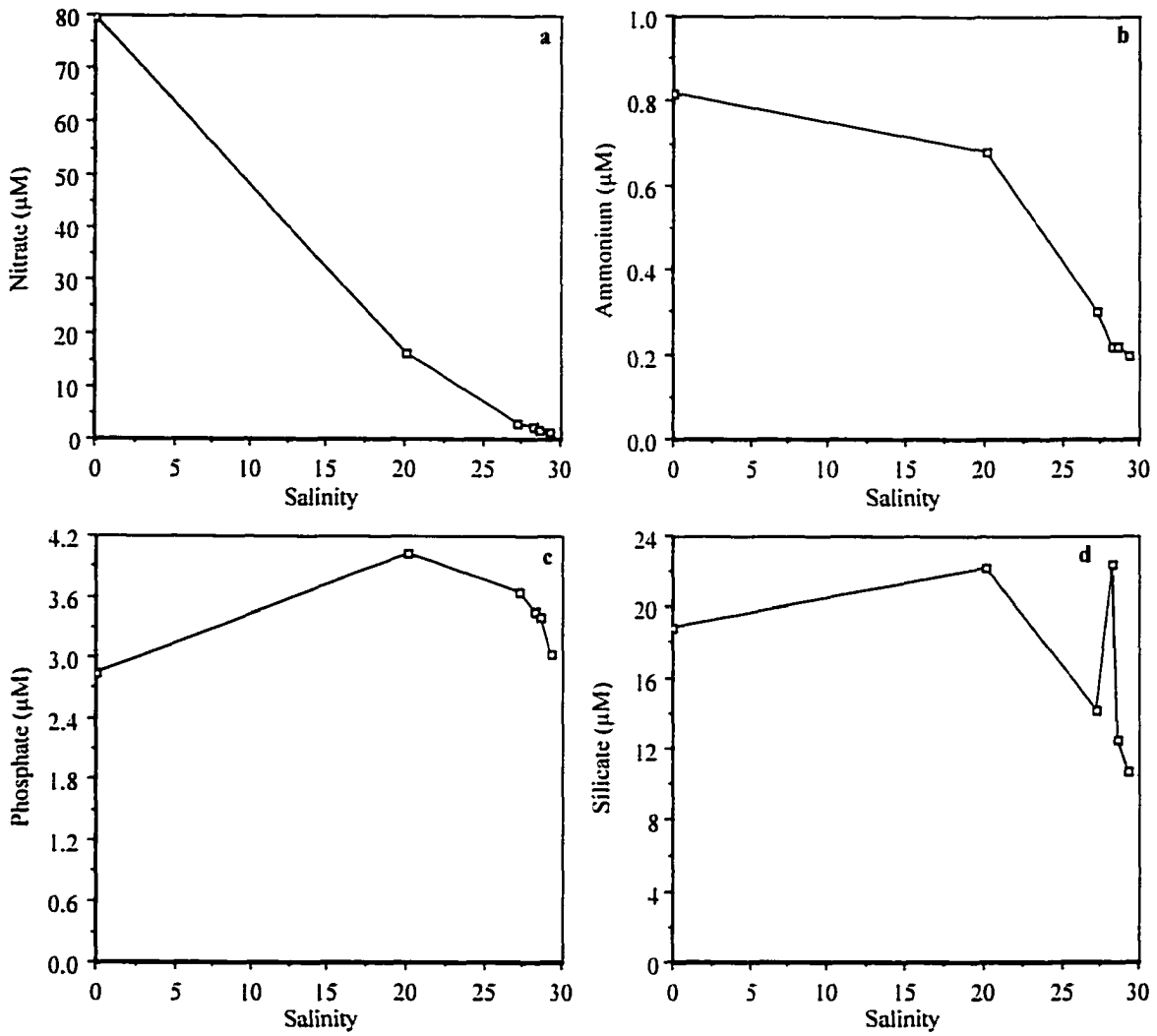

Fig. 43. December 9, 1997. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

This research produced thirteen months of nutrient profiles in order to understand the impact that the continuous flux of freshwater discharge (i.e. groundwater and reservoir discharge) and additional direct and indirect inputs by episodic rainfall events

have on this marine system. These nutrient profiles serve as an aid to better understand the behavior of freshwater borne nutrients within the marine water-column as well as those processes that regulate the input, removal and recycling of these nutrients within Greens Creek. The results of the profiles suggest that biogeochemical processes control the observed nutrient concentrations along the Greens Creek transect rather than the mere physical mixing processes of fresh and seawater.

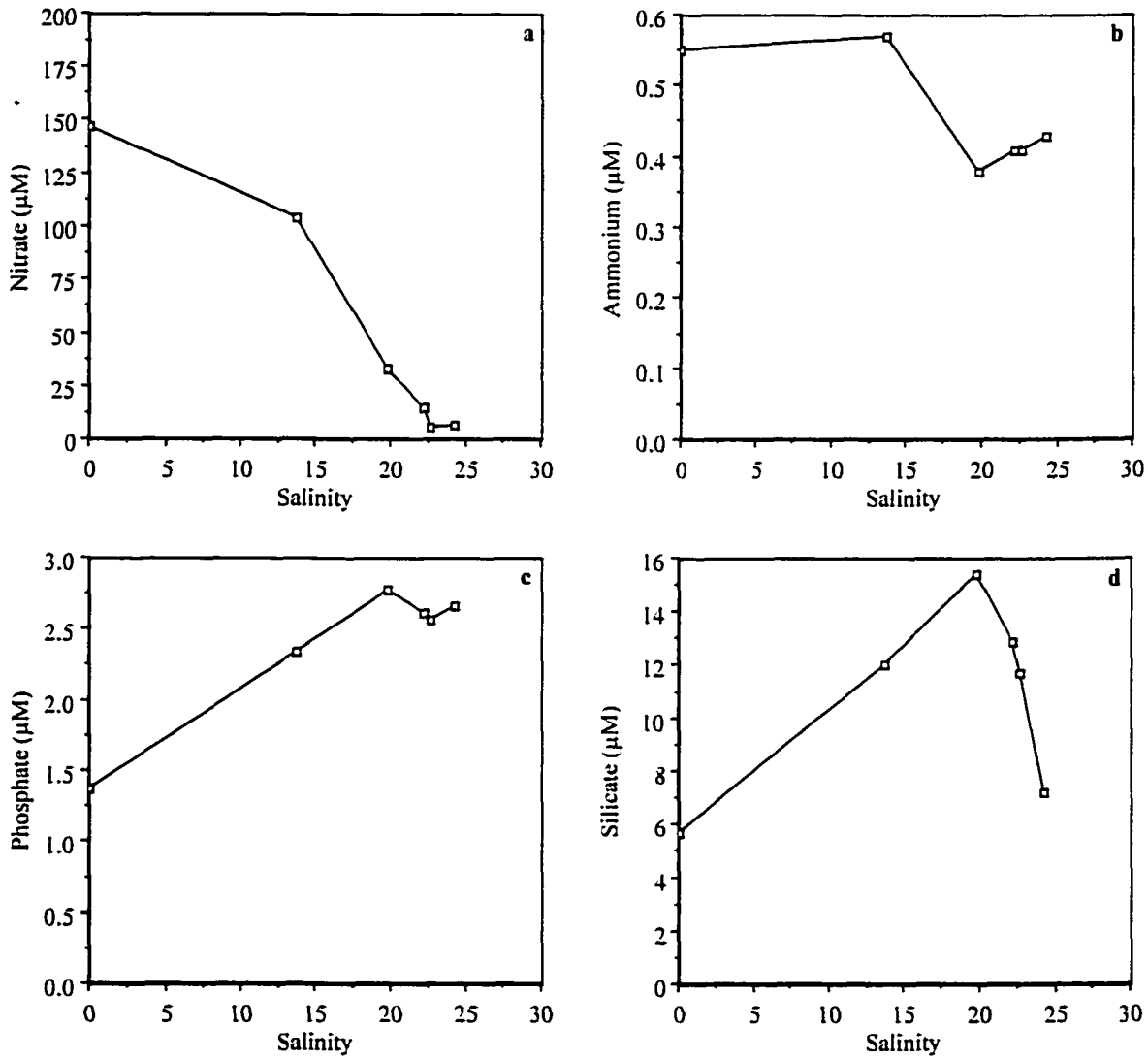

Fig. 44. February 7, 1998. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

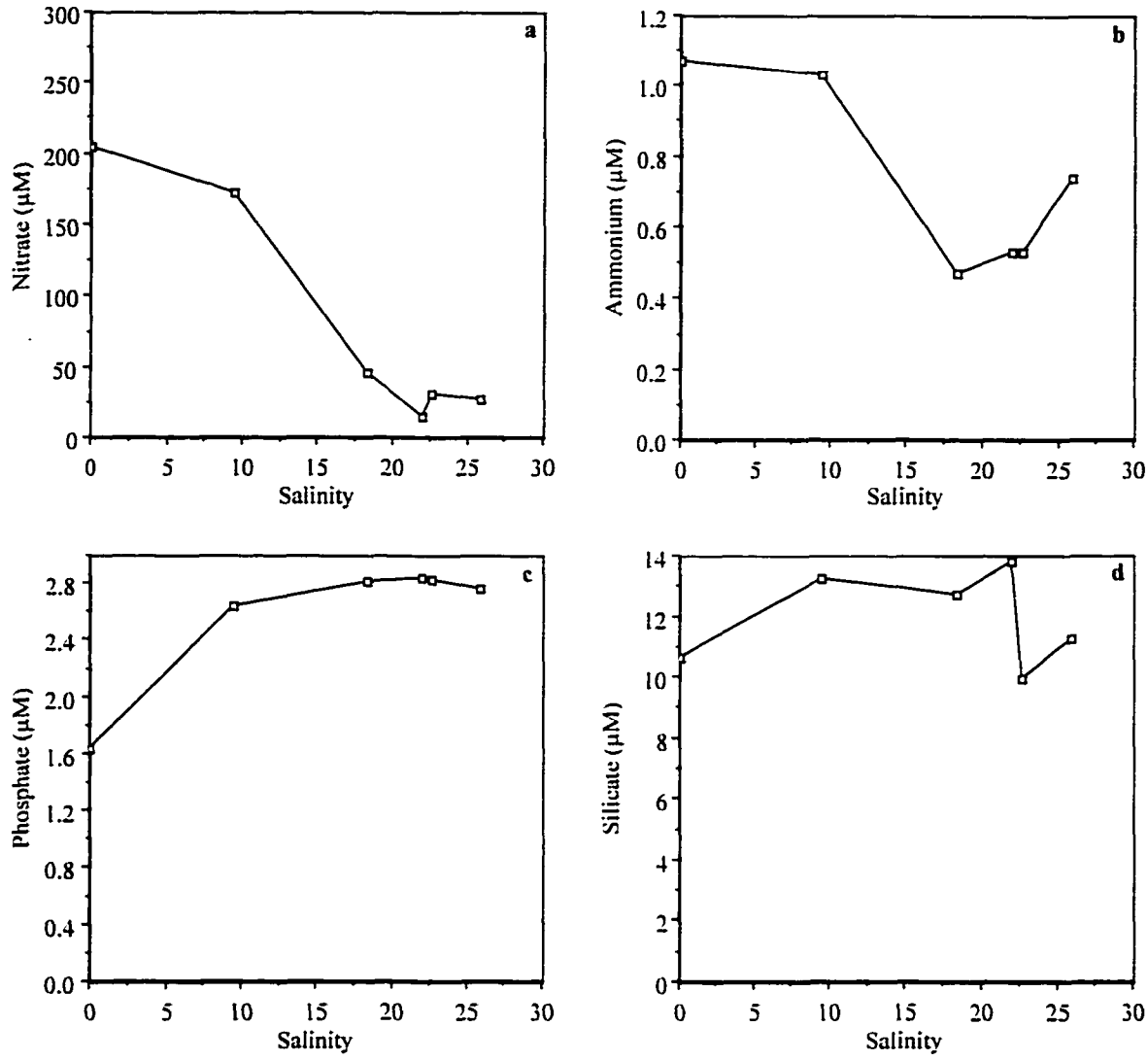

Fig. 45. March 22, 1998. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

The distribution of all measured nutrient species showed concentration fluctuations along the Greens Creek transect on all sampling dates. In general, the details of the NO_3^-, NH_4^+, PO_4^{3-} and SiO_2 nutrient profiles show that over an annual cycle, there are generally only two patterns of nutrient distribution for each measured nutrient.

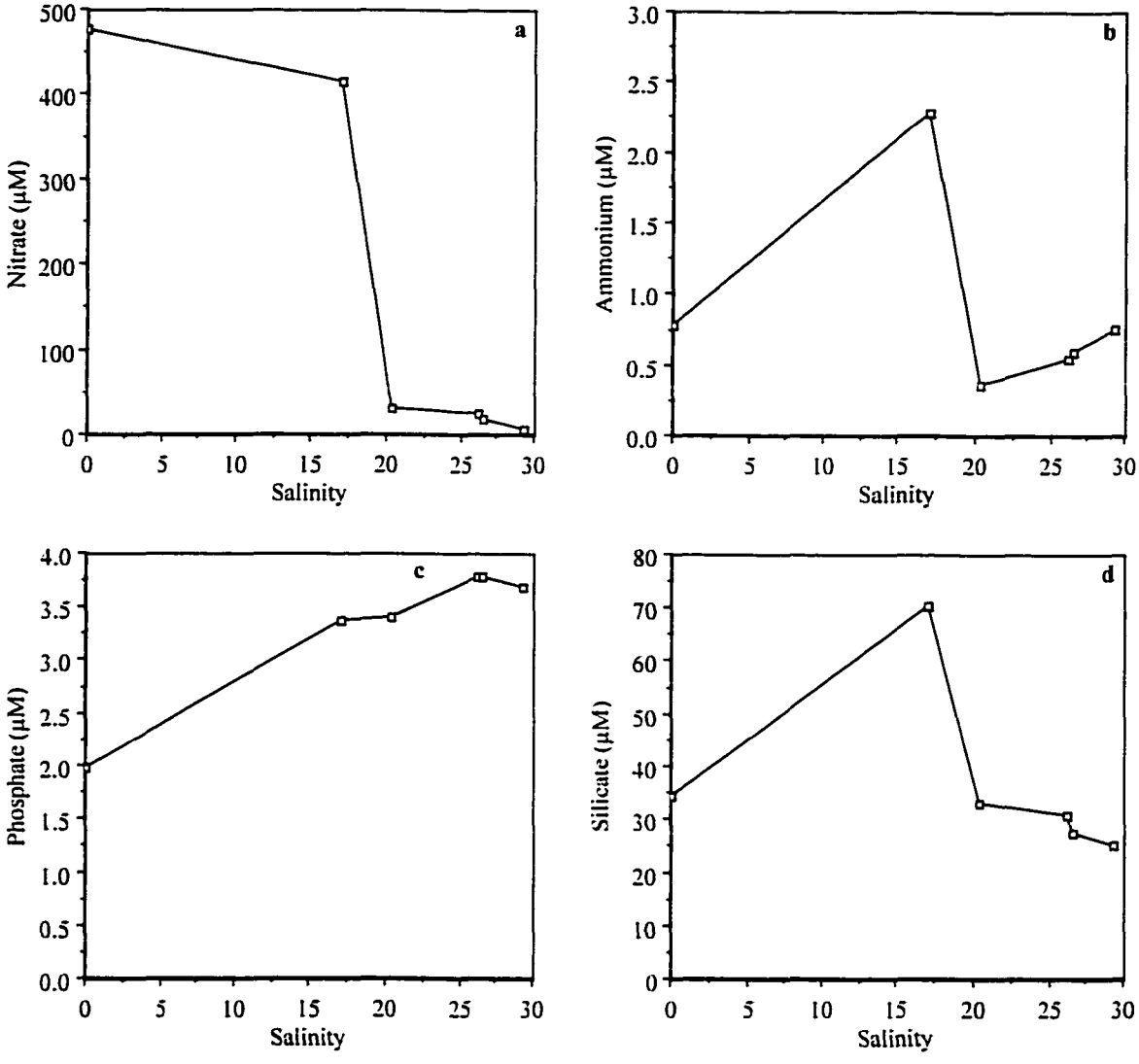

Fig. 46. April 21, 1998. Nutrient profiles of a.) nitrate, b.) ammonium, c.) phosphate and d.) silicate verses salinity along the Greens Creek transect. Refer to Appendix H.1 for standard error values.

A model of estuarine nutrient fluxes through Greens Creek over a two year period demonstrates that this estuary has indeed a series of complex biogeochemical interactions. The interplay of tidal forces, light and nutrients in regulating phytoplankton populations in Greens Creek arises from the dominant seasonal variations in freshwater discharge and the corresponding nutrient composition of that flow. Freshwater discharge

from the reservoir spillway contributes nutrients, particularly N, P, and silica available for phytoplankton uptake. The relationship between nutrient loading and phytoplankton uptake is controlled in part by the observed nutrient distributions and the dynamic salinity conditions in the creek. Furthermore, on a larger scale the extent to which nutrients are exported to the neighboring coastal lagoon depends primarily on how the quantity and nature of the nutrients are modified as they are transported through the creek.

CHAPTER IV
DISCUSSION

On an annual basis, reservoir discharge accounts for an appreciable fraction of the total freshwater inputs deposited directly into Greens Creek simply because the stream is a continuous source of nutrient-rich freshwater to the creek (Fig. 47). Both direct and indirect rainfall provides an important secondary source of nutrients to this system although the inputs are of substantial significance on shorter time scales and only supply episodic nutrient impulses albeit with high nutrient concentrations. Reservoir flow is the most consistent source of freshwater, whereas groundwater discharge is significantly dependent upon tidal fluctuations and recharge rates that are primarily dependent upon rainfall events. The groundwater nutrient input estimates are considered to be somewhat low compared to the actual contribution since this sampling protocol only measured one of the possibly many groundwater seeps that discharge into Greens Creek.

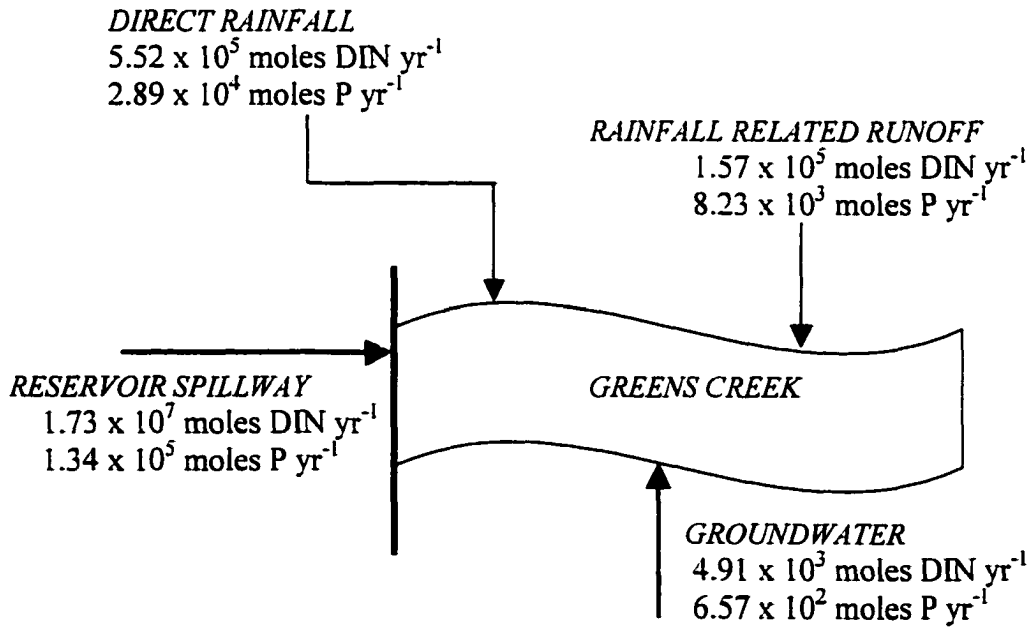

Fig. 47. The quantitative inputs of all observed freshwater sources to Greens Creek. Total nutrient inputs via freshwater sources equals $1.80(*10^7)$ moles DIN $year^{-1}$ and $1.72(*10^5)$ moles P $year^{-1}$.

The estimated yearly loading input rates of freshwater sources to Greens Creek are summarized in Table 21. From these data, it is reasonable to conclude that, on an annual basis nutrient loading of Greens Creek via precipitation, groundwater and primarily reservoir discharge is dominated by nitrate-N with phosphate also being of great importance.

TABLE 21. Yearly loading rates and nutrient composition (% of total input) of all freshwater nutrient sources to Greens Creek are shown. Loading rates are expressed as mg m^{-2} $year^{-1}$.

Loading Rate	NH_4^+	NO_3^-	NO_2^-	Total DIN	PO_4^{3-}
Precipitation	196.32	3816.16	40.48	4052.97	341.23
% Composition	4.83	85.92	0.91	91.66	8.32
Groundwater	643.8	2680.6	289.1	3613.5	1103.8
% Composition	13.6	56.8	6.1	76.6	23.4
Reservoir	4.91(*10^5)	4.98(*10^{11})	4.06(*10^5)	4.98(*10^{11})	167(*10^5)
% Composition	<0.001	99.99	<0.001	>99.99	0.003

The contribution of nitrate-rich freshwater via precipitation, groundwater and reservoir discharge supplies a significant fraction of both N and P directly to the marine portion of Greens Creek. Input rates in conjunction with nutrient measurements determined in this research allow for the comparison of the Greens Creek system with other large river systems to determine if small freshwater creeks input an equivalent concentration of nutrients as large rivers on a per volume basis. Small groundwater driven estuarine ecosystems such as Greens Creek are common features of the

Northeastern United States and differ from their counterparts dominated by large rivers yet little information has been documented on their potential ecological significance. On an annual basis, Greens Creek receives a total of 1.80(*10^7) moles DIN $year^{-1}$ (equates to 3.95 (*10^9) mmol DIN m^{-2} $year^{-1}$) and 1.72(*10^5) moles P $year^{-1}$ (equates to 1.74 (*10^5) mmol P m^{-2} $year^{-1}$) through direct and indirect rainfall events, groundwater and reservoir discharge. Table 22 lists the freshwater N and P input for eight diverse estuarine systems around the globe. The systems represented include a coastal lagoon (Guadalupe Estuary), coastal embayments (Boston Harbor), and an inland sea (Baltic Sea) (Nixon et al., 1996). The estuaries listed represent a wide variety of systems ranging from pristine to highly developed systems, well-mixed to some which have periods of anoxia, and various compositions of intertidal salt marshes. On a per volume basis, other estuarine systems receive less N and P via freshwater sources than Greens Creek (Table 22) which receives a total of 3.95 (*10^9) mmol DIN m^{-2} $year^{-1}$ and 1.74 (*10^5) mmol P m^{-2} $year^{-1}$. Of the selected estuaries compared in this research, the Western Scheldt Estuary receives the largest concentrations of nutrients with a total of 1.34 (*10^4) mmol m^{-2} $year^{-1}$ of N and 1.04 (*10^3) mmol m^{-2} $year^{-1}$ of P (Billen et al., 1985). On a more local perspective, the Chesapeake Bay receives a total of 938 mmol N m^{-2} $year^{-1}$ and 41 mmol P m^{-2} $year^{-1}$ (Boyton et al., 1995) which is still significantly less than the freshwater nutrient input received by Greens Creek. Although the comparison of Greens Creek with other estuaries around the world is useful, the results may be somewhat misleading for several reasons. First, it is often difficult to compare freshwater nutrient imports to estuarine systems since watersheds are typically so large that estimates are based on regional determinations. This causes estimates to be somewhat misleading and often are only conservative estimates not actual measurements. Second, the ability of these systems to retain the available N and P imported to them via freshwater sources is largely a function of flushing rate (i.e. dilution factors). Third, sampling protocol is extremely important since physical and biogeochemical processes act quickly on freshwater entering a system. In order to obtain accurate nutrient measurements, samples must be derived from the freshwater sources themselves and not further downstream. In essence, freshwater nutrient measurements in large estuaries are often extrapolated from sporadic data points since an adequate primary database is often unavailable. Finally, most estuarine systems

only consider large rivers as the primary sources of freshwater nutrients to a system and often the contributions by small streams and tidal creeks are overlooked. Overall, freshwater N and P sources to Greens Creek exhibit significantly greater concentrations of available nutrients than other large estuarine systems. These results show that sampling protocols for large estuarine systems should be altered to incorporate the many smaller systems which it is comprised of. Better information regarding the smaller systems will ultimately provide a better understanding of the many interactions that occur in the larger estuarine system.

TABLE 22. Nitrogen and phosphorus inputs to several locations via freshwater discharges from a variety of sources. Units are expressed as mmol m^{-2} $year^{-1}$ for both N and P. Data compiled by Nixon et al. (1996).

Location	N	P	Reference
Baltic Sea	191	4.1	Swedish EPA (1993)
Chesapeake Bay	938	41	Boyton et al. (1995)
Narragansett Bay	1960	115	Nixon et al. (1995)
Guadalupe Estuary	2018	171	Brock et al. (1995)
			Longley (1994)
Potomac Estuary	2095	44	Boyton et al. (1995)
Ochlockonee Bay	5992	-	Seitzinger (1987)
Boston Harbor	9095	660	Alber & Chan (1994)
W. Scheldt Estuary	13400	1040	Billen et al. (1985)

Furthermore, it is important to state that nitrate concentrations in a variety of freshwater sources over the long-term have been shown to be continually increasing due to increased combustion of hydrocarbon fuels and other industrial sources. This trend was evident in all of the aspects of the freshwater results of this research. The details presented in this research show the importance in understanding upland characteristics

including freshwater sources in order to understand the health and nutrient availability in the downstream estuarine environment. It is also important to realize that this research focuses on freshwater nutrient sources and other factors such as regeneration and recycling of nutrients within the water-column; although, sediments may also play a significant role in providing nutrients which are available to phytoplankton for production within this system. Now that the magnitude of each of the freshwater nutrient sources to Greens Creek have been quantified, it is time to focus on the biogeochemical processes characterizing each of the observed sources.

Precipitation

The exact role and importance of atmospheric deposition in many ecosystems is still uncertain. It is the present belief that a significant fraction of nutrients, total nitrogen in particular, are entering coastal and marine ecosystems through atmospheric depositions. Recent research in numerous estuarine, coastal, and oceanic regions of the world, have shown that atmospheric N does indeed provide a significant source of nutrients available for new phytoplankton production. Paerl (1997) reported that 20 – 40% of new N inputs to coastal waters are of atmospheric origin. More importantly, rainfall serves as an external nutrient source capable of altering N:P ratios which result in changes in the phytoplankton community within many systems (Jickells, 1995). One of the main objectives of the research is not only to define the quantity of atmospheric deposition received by the Greens Greek watershed but to also investigate the availability of rainfall as a nutrient source for the phytoplankton population within Greens Creek.

The importance of atmospheric nutrients for primary production in Greens Creek depends on the biological availability of the nutrient species in rainfall events. In turn, the availability of atmospheric nutrients is controlled by many factors including volume of rainfall, duration of rainfall, temporal variations, and atmospheric mixing. Results of this 21-month study showed total rainfall volume was greater during 1998 than 1997 (Fig. 10) with volumes measuring 49.47 and 33.76 inches respectively. The difference in rainfall volumes between the two sampling years is partly attributable to the occurrence

of several storms including tropical storm Josephine which singularly unloaded a total of 3.91 inches of rainfall in a single event on October 8, 1996.

There was no apparent seasonal pattern in the rainfall volume over the study period although it is clearly evident that nutrient concentrations varied greatly among rainfall events. Many researchers have concluded that nutrients are swept out of the atmosphere with the first few centimeters of rainfall; therefore, as rainfall duration increases then nutrient concentrations tend to decrease. Maximum concentrations for all measured nutrient species (NH_4^+, NO_3^-, NO_2^-, and PO_4^{3-}) are centered on rainfall volumes of approximately 1 – 2 cm suggesting that this data shows some seasonal variability in individual nutrient concentrations. The variations to a large extent are dependent upon rainfall volume; therefore, these results also exhibit the general trend of decreased nutrient concentrations with increased rainfall duration similar to the conclusions of other researchers (Valiela et al., 1978; Correll and Ford, 1982).

This study also concluded that nitrate was the primary inorganic nitrogen species loaded to the watershed by precipitation followed by ammonium with nitrite always being of least abundance. No apparent seasonal trend was evident for nitrate concentrations, although there appears to be an increase in nitrate concentrations from year to year (1997 – 1998) similar to the results of other researchers. According to several researchers (Valiela et al., 1978; Correll & Ford, 1982; Jordon et al., 1995) NO_3^- concentrations have been increasing in atmospheric deposition for the past 20 years due to increased anthropogenic N oxide emissions originating from increased rates of hydrocarbon fossil fuel combustion. Due to the eastward advection of urban and agricultural nitrogen emissions from the Ohio Valley (Galloway et al., 1984), it is not surprising that the increased nitrate affects are being detected in the rainfall events occurring on the Eastern Shore. Overall, this increasing nitrate loading may have serious implications on future eutrophication and acidification concerns of the Eastern Shore estuaries.

Ammonium concentrations show an obvious seasonal pattern in which concentrations are lower than NO_3^- throughout the year except when NH_4^+ concentrations reach maximum values during the summer months (June – August). The NH_4^+ summer maxima was more evident for the 1997 sampling year than for 1998. However, it is

suspected that the ammonium peak was beginning just as the sampling was discontinued in the early summer of 1998; therefore these results are somewhat inconclusive and one can only speculate that the occurrence of a summer NH_4^+ peak is repeated in the second year of the study. It is believed that the high NH_4^+ peak apparent during summer months is due to the treatment of effluent from chicken processing plants located on Virginia's Eastern Shore. Poultry waste is currently an unregulated action of the poultry industry and can potentially cause substantial water quality problems in Virginia. The preferred method of treatment for processing wastewater effluent is to use it as a fertilizer in land applications. In the treatment method effluent is applied to the land typically in the early spring months using spray techniques, which allows for increased volatilization into the atmosphere where it then accumulates and is precipitated out during rainfall events. Nitrite was the least abundant N-species measured during all sampling events with concentrations showing large variations similar to NO_3^- and NH_4^+. There is no apparent seasonal pattern of nitrite concentrations in rainfall events.

Phosphorus is often neglected from precipitation research since the common misconception is that there is no significant atmospheric source. Although there is no globally significant source of atmospheric P, there can be a local land use P source (i.e. farmlands). Since the Eastern Shore is primarily characterized by prime agricultural lands, fertilization by farmers may contribute to P levels detected in rainwater. This is a concept often omitted in global atmospheric studies, yet it is a theory which dates back over 30 years (Reimold and Daiber, 1967). In general, P should be considered in precipitation research because it does have a significant role in marine primary productivity and can be a significant component of rainfall. The results of this research conclude that phosphate concentrations varied greatly among rainfall events but a seasonal pattern is evident. Maximum concentrations were consistently detected during summer months similar to the results derived for NH_4^+ summer peaks (June – August) for both sample years due to the desorption of reactive dissolved phosphate from organic particulates during airborne transport processes. Although summer 1998 values are significantly higher than those seen during the previous summer, there is believed to have been some contamination of the samples during analysis due to elevated levels of P in the

deionized water system. The elevated values were not discarded since they repeat the general trend of maximum values during the summer months.

All measured nutrients showed a large concentration range among all collected rainfall events over the sampling period with DIN concentrations representing the greatest total concentration of N. Total volume weighted N concentrations were measured to be approximately 3794, 737, and 55 μM for NO_3^-, NH_4^+, and NO_2^-, respectively. Ammonium and nitrate concentrations were the most significant form of inorganic N with mean concentrations equivalent to 10.10 and 51.97 micromoles respectively. Nitrite concentrations were consistently the most negligible N species with volume weighted concentrations ranging from 0.01 to 6.08 μM for all collected events.

Natural rainfall has a high fertilizing potential for phytoplankton due to its ability to supply DIN and other co-limiting nutrients such as P simultaneously. Total DIN loading into the Greens Creek watershed by rainfall accounted for approximately 92% of the total atmospheric composition (Fig. 48). Other studies have concluded similar results in which atmospheric DIN (NO_3 + NH_4) contributes 25-35% of the total nutrient input (Tyler, 1988; Fisher & Oppenheimer, 1991; Scudlark & Church, 1993) with NO_3 concentrations typically greater than NH_4. Ammonium (< 5%) and nitrite (<1%) contributed very little as compared to nitrate. Phosphate concentrations were estimated to be ~8%, a large contribution to the total rainfall composition, which suggests that fertilization by local farmers may contribute to elevated P levels detected in rainwater. These results conclude that rainfall affecting the Greens Creek watershed is composed primarily of N (91.66%) as compared to P (8.32%) with NO_3^- accounting for approximately 86% of the available N in precipitation.

A specific goal of this research was to not only assess the temporal variability associated with atmospheric fluxes but to also investigate the nutrient rainfall contribution available to the Greens Creek phytoplankton community. Atmospheric deposition may contribute a significant fraction of both N and P required for algal growth within this system especially on short (hours) time scales. Event and yearly fluxes were calculated for all measured nutrient species in order to investigate the rainfall contribution of external nutrients to the Greens Creek watershed. These results conclude that on a yearly basis nitrate (~3816 mg m^{-2} $year^{-1}$) is the primary inorganic N species

loaded to the watershed with phosphate (~34 mg m^{-2} $year^{-1}$) also being of great significance. These results present evidence on why P should be considered in all precipitation research on the Eastern Shore as it does constitute a significant component of rainwater.

These results show that direct rainfall inputs are particularly important to surface water primary productivity since direct rainfall not only percolates through the surrounding watershed, but is also directly deposited to the surface and immediately available for uptake. It is important to note that anthropogenic fossil fuel emissions are contributing an increasing supply of N to the atmosphere every year; therefore, emission standards should play a key role in developing management proposals aimed at reducing nitrogen loading to coastal waters.

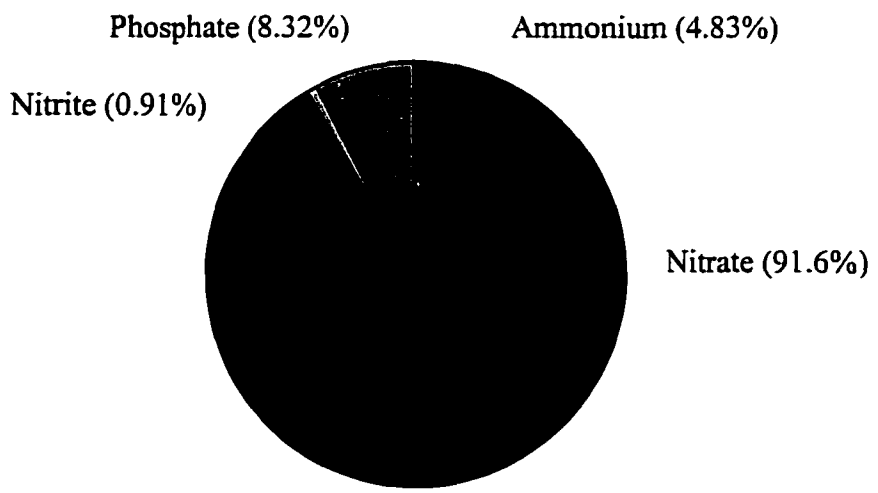

Fig. 48. Percent composition of total atmospheric fluxes for each measured nutrient species in Eastern Shore precipitation events.

Overall, atmospheric deposition (wet deposition only) contributes ~4053 mg DIN m^{-2} $year^{-1}$ to the Greens Creek watershed as bioavailable forms such as NO_x and NH_4^+. Globally, precipitation events can contribute from 300 to >1000 mg N m^{-2} $year^{-1}$ to

coastal waters and ~35 Tg N yr^{-1} to the worlds oceans (Paerl, 1997). The literature on atmospheric deposition around the globe exhibits a wide range of nutrient contributions to the coastal oceans. The values determined for precipitation events which contribute to the Greens Creek watershed are on the high end of the 300 to >1000 mg N m^{-2} $year^{-1}$ range. The rainfall events on the Eastern Shore which contribute to the nutrient composition of the coastal ocean is believed to be an accurate estimation. It has been shown that the local and regional landuse practices have a strong influence of precipitation composition and it is important to remember that rainfall composition and quantity can be highly variable from year to year.

Rainfall Runoff

Rainfall related runoff is a significant component of nonpoint source nutrient loading to this ecosystem. Based on an average of 124.8 storms per year yielding an average storm rainfall volume of 0.39 inches per event, an average storm runoff volume was calculated to be 2.01 x 10^4 m^3 for the Greens Creek watershed. This equates to annual average storm runoff of 2.50 x 10^6 m^3 $year^{-1}$ that contributes a significant amount of new biologically available nutrients to the creek. Even though the Greens Creek watershed is characterized as a combination of open space and single family residences, a significant amount of runoff escapes the watershed and becomes deposited directly into the photic zone of Greens Creek. The watershed retains a significant portion of the total nutrient rich freshwater runoff in the upland due to the low pavement area where it then serves as a mechanism for groundwater recharge. In essence, the retention capability of the watershed is primarily dependent upon land use, although other factors such as localized rainfall rate and volume, plant uptake, and evaporation processes do play a large role (Correll et al., 1992; Scudlark and Church, 1993; Wong et al., 1997). The results of rainfall related runoff models such as this allow local farmers to determine which best management practices (BMPs) should be employed and where these BMPs will be most beneficial. For Greens Creek, rainfall related runoff through the watershed contributes 2.42 (*10^3) mg DIN m^{-2} $year^{-1}$ (1.57 x 10^5 moles DIN $year^{-1}$) and 97 mg P m^{-2} $year^{-1}$ (8.23 x 10^3 moles P $year^{-1}$). This research concludes that nonpoint source pollution

such as rainfall related runoff contributes a significant amount of biologically available nutrients directly to Greens Creek. Compared to the annual precipitation rate of 8.79(*10^6) m^3 of the Greens Creek watershed, the annual average storm runoff comprises 28% of the total rainfall volume which is either indirectly transported into the creek where it then is available for phytoplankton uptake or filters through the sediments recharging groundwater.

Groundwater

Virginia's Eastern Shore is a unique environment compared to the surrounding Chesapeake Bay area. The Eastern Shore has no rivers associated with it; therefore, it is quasi-dependent upon groundwater for its freshwater (Richardson, 1994). However, both direct and indirect atmospheric deposition does supply the Eastern Shore with episodic impulses of freshwater. The primary focus of this section of research is to not only quantitatively delineate sub-surface groundwater discharge as a nutrient source to Greens Creek but to also understand the impact it has on phytoplankton production. Sub-surface shallow groundwater, ~1 meter below the ground surface, flows from upland recharge areas through local flow paths where it is then able to discharge directly to Greens Creek through the sediment-water boundary (Speiran, 1996). Species composition of groundwater is an important factor in determining the resultant phytoplankton response to nutrient input by groundwater. Groundwater can cause loading-dependent alterations in the receiving creek waters that in turn causes significant changes in nutrient concentrations and thus greater phytoplankton production (Johannes, 1980; Sewell, 1982; Millham and Howes, 1994; Valiela et al., 1992). Shallow aquifers, such as the one investigated in this research, exhibit strong relationships with precipitation and the overlying land use (Hallberg, 1986).

Total DIN concentrations in all shallow groundwater wells (beach, central and inland wells) exhibited large concentration measurements over the sampling period. The data displays a seasonal DIN pattern with maximum concentrations occurring in the spring months (March – May) and minimum concentrations occurring during the winter months (December – February). The observed maximum DIN concentrations are

attributable to two controlling factors: 1.) spring rainfall events input a significant amount of nitrate to the watershed and 2.) N-rich fertilizer applications are applied to the upland agricultural fields in the late winter months (January – February) which subsequently recharge underlying groundwater aquifers. In addition, shallow groundwater DIN concentrations increased from 1996 to 1998 similar to the results discussed for nitrate increases in rainfall events due to the long term increases in the industrial combustion of fossil fuels. This long-term increase in groundwater N concentrations shows the effect that atmospheric deposition and upland land use has on groundwater recharge and nutrient composition.

Dissolved inorganic nitrogen in groundwater wells was characterized primarily by nitrate (56.8%) and ammonium (13.6%) with low concentrations of nitrite (6.1%). Concentrations of NH_4^+ and NO_2^- were generally highest in the beach well, directly adjacent to Greens Creek, as compared to both the inland and central shallow groundwater wells. This suggests that nitrate reduction is occurring along the well transect as groundwater flows toward the creek sediment-water boundary. The beach well site may have a more abundant amount of organic matter than the other well sites which promotes the rapid depletion of available dissolved oxygen in the aquifer and reduction of nitrate to ammonium. Available nitrate is reduced to nitrogen gas or ammonia when dissolved oxygen concentrations are limiting. Researchers have shown that nitrate levels in groundwater underneath forested buffer areas are generally elevated due to recharge through agricultural fields (Speiran et al., 1996). Typically, as distance from the overlying agricultural field increases, age of the groundwater also increases allowing for denitrification processes to convert NO_3^- to N_2 due to low oxygen content of the groundwater. The results of this research conclude that groundwater wells closest to the agricultural fields and nearby forested areas exhibit higher levels of nitrate than wells closest to the creek. Conversely, wells furthest from the fields are primarily characterized by higher NH_4^+ and NO_2^- concentrations. Low dissolved oxygen measurements and corresponding low nitrate concentrations in the beach well provide evidence of denitrification and explain the high concentrations of NH_4^+ and NO_2^-. Concentrations of species specific N in groundwater are affected by many variables: amount of available N, volume of water percolating through the overlying sediment

layers that recharges groundwater supplies, and oxygen concentrations within the aquifer which control the potential for nitrate reduction (Johannes, 1980; Capone and Bautista, 1985; Hallberg, 1986).

Total DIN accounted for 76.6% of the total measured nutrient composition entering Greens Creek through shallow groundwater discharge with phosphate concentrations accounting for only 23.4% of the total discharge. Measured groundwater PO_4^{3-} concentrations were generally low, similar to the results of Valiela et al. (1990), and also varied among sampling dates with no evident seasonal trends. Increased variability is often associated with groundwater P levels since phosphate is readily adsorbed by sediment surfaces and thus removed from groundwater. Concentrations of PO_4^{3-} were greatest in beach wells with concentrations decreasing in central and inland wells as distance from the creek increased. These results provide evidence of tidal pumping into these sub-surface shallow groundwater wells. The changes in the tidally active region of the aquifer promote fluctuating groundwater table elevations and hydraulic gradients thus controlling freshwater discharge into Greens Creek (Staver and Brinsfield, 1996). These tidal pumping processes allow for the mixture of P-limited freshwater and P-rich saltwater to enter the groundwater aquifer. The extent of tidal pumping is evident in the spatial differences in PO_4^{3-} concentrations along the well transect with concentrations decreasing from the beach to inland well.

In order to investigate the nutrient contribution available to the phytoplankton community in Greens Creek, mean hourly and yearly fluxes were calculated for all measured nutrient species using an average discharge rate of 2.0 L m^{-2} $hour^{-1}$ (Robinson et al., 1997). Reay et al. (1992) report groundwater discharge rates of 0.02 to 3.69 liters m^{-2} hr^{-1} for Cherrystone Inlet, on Virginia's Eastern Shore (Table 23); therefore, the average discharge of 2.0 L m^{-2} $hour^{-1}$ used in this research is a conservative estimate. The results of this study conclude that nitrate was the predominate DIN-species loaded (Giblin and Gaines, 1990; Reay et al., 1992; Speiran et al., 1996) to the marine portion of Greens Creek, followed by ammonium and phosphate. On an annual basis, groundwater loads a large contribution of N to Greens Creek with DIN species equating to 2680.6, 643.8 and 289.1 mg m^{-2} $year^{-1}$ for NO_3^-, NH_4^+, and NO_2^- respectively. Groundwater discharge and subsequent loading rates vary a great deal in the short term due to

fluctuations in tidal elevations but in the long term are controlled by seasonal changes in groundwater recharge rates (Capone and Bautista, 1985; Valiela et al., 1990; Staver and Brinsfield, 1996). Despite short-term changes in discharge rates, groundwater discharge serves as an appreciable source of freshwater to Greens Creek.

TABLE 23. Groundwater discharge rates from selected locations. Rates are expresses as liters m^{-2} hr^{-1}.

Location	Discharge Rate	Reference
Virginia's Eastern Shore		
Cherrystone Inlet	0.02 - 3.69	Reay et al. (1992)
Cherrystone Inlet	2.0	Robinson et al. (1997)
Eyreville	0.11 – 1.45	Reay et al. (1992)
Eyrehall	0.07 – 0.34	Reay et al. (1992)
Steelmans	0.02 – 0.61	Reay et al. (1992)
Old Castle	0.07 – 0.18	Reay et al. (1992)
Virginia's Coastal Plain	0.25 – 0.42	Harvey & Odum (1990)

Nitrate rich rainfall recharges the shallow groundwater aquifer and as groundwater slowly flows through the watershed it becomes altered due to the dissolved oxygen availability, overlying land use, flow rates, and soil and aquifer compositions. Groundwater nitrate concentrations ranged from as low as 0 μM to as high as ~70 μM over the sampling period. Table 24 shows nitrate concentration ranges for various locations and gives evidence that NO_3^- concentrations can vary greatly among sites. The range of nitrate concentrations measured in groundwater discharging to Greens Creek is somewhat smaller as compared to other locations (Table 24). Similar to the nitrate results, ammonium (13.6%) constituted an appreciable component of groundwater composition discharging to Greens Creek. Phytoplankton generally assimilate available NH_4^+ at a higher rate than NO_3^- since they more efficiently utilize NH_4^+ as an energy

source. Therefore, the bioavailability of both nitrate and ammonium in groundwater is ecologically important for phytoplankton production within the creek.

TABLE 24. Ranges of groundwater nitrate concentrations from various coastal aquifers and groundwater discharging into coastal waters. Data complied by Valiela et al. (1990).

Location	NO3- Concentration (μM)	Reference
Groundwater in coastal aquifers		
Orleans, MA, US	0 – 393	Gaines et al. (1983)
N. Carolina, US	1 – 2250	Gilliam et al. (1974)
Falmouth, MA, US	0.7 – 693	Meade & Vaccaro (1971)
Cape Cod, MA, US	0 – 450	Frimpter & Gay (1979)
Long Island, NY, US	8 – 610	Bowman (1977)
Groundwater discharge into coastal waters		
Great Sippewissett Marsh, MA, US	10 – 100	Valiela et al. (1978)
Town Cove, MA, US	9.7 – 107	Giblin (1983)
Agana Bay, Guam	178	Marsh (1977)
Western Is. of Hawaii	29 – 91	Kay et al. (1977)
Swan River Estuary, W. Australia	115 – 380	Johannes (1980)
Discover Bay, Jamaica	88 – 250	D'Elia et al. (1981)

It is important to remember that there is a high degree of variability associated with groundwater discharge into estuaries due to tidal fluctuations and a large percentage of the available discharge may be intercepted by the surrounding marshlands (Harvey and Odum, 1990) where it then serves to enhance marsh productivity. Groundwater flowing perpendicularly into Greens Creek contributes 4.91($*10^3$) moles DIN $year^{-1}$ and 6.57($*10^2$) moles P $year^{-1}$. In addition, this research has also shown that direct groundwater discharge contains higher dissolved inorganic nitrogen levels than that of

the receiving creek water; therefore, groundwater discharge into Greens Creek appears to be of significant ecological importance and should be considered in future water quality assessments of other estuarine systems.

Reservoir Discharge

In addition to measuring the nutrient content and loading rates of atmospheric deposition and sub-surface shallow groundwater, reservoir nutrient composition and discharge rates were also investigated and determined to be the most significant freshwater nutrient source to Greens Creek. Similar to the results for rainfall and groundwater, nutrient concentrations show a great deal of temporal variability over the sampling period. Reservoir DIN concentrations were greatest during the 1998 sampling months as compared to the previous years. The increase in fossil fuel combustion measured as the long term increase in nitrate concentrations is implicated in all aspects of this research (i.e. rain events, groundwater discharge and reservoir discharge) consistent with results of past researchers (Valiela et al., 1978; Correll & Ford, 1982; Jordon et al., 1995). In general, the mean reservoir DIN concentration (161.74 μM) was roughly 2.5 times greater than the average rainfall DIN concentrations (62.82 μM) and six times greater than the average groundwater DIN concentrations (25.18 μM).

Dissolved inorganic nitrogen inputs from the reservoir discharge into Greens Creek are characterized as nitrate-rich (>99.99%), similar to rainfall events, with ammonium and nitrite concentrations contributing very little to the total available inorganic N. Winter months are characterized by low NO_3^- reservoir concentrations increasing to maximum concentrations as summer months approach. Once maximum values are reached during summer months, concentrations begin to decrease through the fall months back to minimum concentrations in the winter. This seasonal pattern coincides with the elevated nitrate levels reported in the previously discussed atmospheric deposition events during summer months. Reservoir nutrient composition and discharge rates are governed by the surface flow in the upland freshwater portion of Greens Creek that is fed primarily by nitrate-rich groundwater and episodic rainfall events.

Ammonium concentrations were consistently greater during the late summer and early fall of 1996 as compared to the following year. The appearance of the late summer - early fall NH_4^+ maximum (August through October) over the study can indicate two possible scenarios. First, during summer months when reservoir discharge is low, rainfall and groundwater discharge are of ecological importance because they provide external N sources to the creek. As discussed earlier, NH_4^+ concentrations in rain events reach maximum values during the summer months (June – August); therefore, there is the possibility of a time-delayed effect from when the events occur and when the elevated concentrations are transported via surface runoff to the reservoir. Second, during summer months when temperatures are high and dissolved oxygen levels are typically low or depleted, elevated nitrate levels are biochemically reduced, or denitrified, to ammonia. Therefore, the reservoir experiences elevated levels of both NO_3^- (due to nitrate-rich groundwater) and NH_4^+ (due to ammonium-rich rainfall and denitrification processes) during summer months. The mean NH_4^+ reservoir concentration for the sampling period is approximately 1.5 times less (1.97 μM) than the average NH_4^+ concentration determined for sub-surface shallow groundwater contribution. More interestingly, the mean rainfall concentration is greater than 5 times the reservoir mean. This data suggests that summer atmospheric deposition events in combination with high summer temperatures and low O_2 in the reservoir play a large role in the N-speciation occurring within the reservoir.

Similar to the reservoir discharge NO_2^- results, PO_4^{3-} concentrations also revealed no evidence of seasonal trends. Overall, mean phosphate concentrations are comparable for rainfall, groundwater and reservoir discharge are 3.29, 1.31, and 1.25 μM, respectively. Recall that phosphate is readily adsorbed by sediment surfaces; therefore, reservoir and groundwater PO_4^{3-} concentrations are generally lower than those of rainfall. Freshwater systems are generally P-limited because phosphate is easily bound to riverine sediments where it is buried and thus unable to play an active role in short term biogeochemical processes. This adsorption of PO_4^{3-} onto organic matter decreases P concentrations in the water-column and reduces PO_4^{3-} availability for phytoplankton uptake.

The composition of the reservoir water discharging into Greens Creek is characterized primarily by nitrate (>99.99%) with ammonium and nitrite contributing very little (<0.001) to the total DIN composition. Phosphate accounted for the remaining 0.003% of the total measured nutrient composition. The reservoir, which serves as a collector of freshwater stream flow generated directly from upland agricultural activities, is capable of discharging nitrate-rich freshwater into Greens Creek at an average rate of 3.39 $m^3 s^{-1}$ based on the spillway current velocity measurements taken at the spillway. This rate is significantly larger than the rate used for determining groundwater discharge into Greens Creek (2.0 L $m^{-2} hr^{-1}$). The mean yearly loading rate results determined for the reservoir spillway conclude that the reservoir spillway at the head of Greens Creek discharges approximately 4.98(*10^{11}), 4.91(*10^5), and 4.06(*10^5) mg m^{-2} $year^{-1}$ of NO_3^-, NH_4^+, and NO_2^- respectively. In addition to DIN, the reservoir discharges 167(*10^5) mg m^{-2} $year^{-1}$ of phosphate directly into the creek. Overall, the reservoir is the primary means of nutrient input to the estuary of Greens Creek in addition to being the dominant nutrient source for phytoplankton production within this system.

Tidal Flushing

Tidal flushing in an estuarine system such as Greens Creek plays a large role on the response of phytoplankton populations to varying nutrient inputs. This research concludes that tidal range and associated processes such as tidal mixing and current velocity greatly influence phytoplankton biomass within this microtidal system (Monbet, 1992). The results of the 30-hour ADCP study at station 4 near the mouth of Greens Creek show that there are large variations in current velocities at the inlet of the creek ranging from as low as 0.6 cm/s to as high as 79.0 cm/s. Overall, maximum velocities were greater during the flood (~ 79.0 cm/s) than the ebb (~70.4 cm/s). These results show that the flood at the entrance of Greens Creek is more asymmetrical while the ebb is only slightly asymmetrical (Nichols and Biggs, 1985). The asymmetrical nature of the flood tide provides evidence that it dominates and has greater mixing energy associated with it than the ebb tide. The ebb tide has less mixing energy associated with it due to the

more symmetrical nature of the flow and therefore is characterized by more stratified flow conditions.

Salinity measurements over the 30-hour tidal study show that tidal exchange produced fluctuations a ~4 ppt change in the observed salinity with values ranging from 24.628 during low tide conditions to as high as 28.501 directly following peak recharge. Obviously, flood tides bring in higher saline water to the creek with ebb tides allowing the freshwater signal to be most evident. Variations in surface salinity represent seasonal variations in freshwater inputs which correspond to wet and dry periods. In general, low surface salinity typically controlled by increased rainfall events and/or volumes characterizes wet periods. The opposite holds true for dry periods that are characterized by higher surface salinity due to decreased volumes of rainfall. The details of this research show apparent alterations between wet and dry periods over the sampling period although there is no evident seasonal pattern.

It is evident from what many researchers have already learned about estuaries, that freshwater river flow causes the downstream movement of the salt water wedge and also generally increases water circulation within the basin (Dyer, 1973). Based on the 30-hour current velocity measurements and a basin capacity of Greens Creek (~0.949 ($*10^6$) m^3), hydraulic turnover time (HTT) of the Greens Creek basin was estimated to be 7.1 hours. This is the time required to replace the existing freshwater in the estuary at a rate equal to the river discharge. This implies that increased freshwater discharge is accompanied by a more rapid exchange of freshwater with the intruding seawater (Dyer, 1973). In addition to the hydraulic turnover time, the estuary number (e) describes the nature of the water as it passes through the inlet of Greens Creek. An estuary number equal to 0.029 was calculated and characterizes the creek water ebbing toward the inlet as having stratified flow due to the influx of freshwater primarily by reservoir and groundwater discharge.

Overall, tidal exchange in Greens Creek is a constant battle between stratification and destratification, or mixing, processes. Ebbing tides are continually trying to stratify the water column due to the continuous influx of freshwater from the reservoir spillway. On the other hand, flood tides characterized by well-mixed high saline water are trying to destratify the water column and break down the salt-water wedge due to the increased

tidal energy associated with the incoming tides. The effects of tidal mixing on phytoplankton populations are often not direct relationships. In general, the effects are interpolated through fluctuations in light penetration through the water column (Monbet, 1992). Changes in light availability typically occur on faster time scales than phytoplankton cells can adjust their physiology. Therefore, in systems such as Greens Creek where tidal mixing is high and stratification – destratification processes of the water column are constantly acting as opposing forces, the phytoplankton biomass is often low due to high tidal energy which promotes increased turbidity within the system.

Light penetration through the water-column is regulated primarily by incident light, suspended particulate matter, and the depth of the surface mixed layer. Light is often considered one of the limiting factors for phytoplankton growth in estuarine systems (Pierce et al., 1986) yet it is not always considered in water quality research. Solar radiation is simply the driving force in the conversion of inorganic to organic compounds during photosynthesis. This research concluded that the flood velocities were greater and slightly more asymmetrical than the ebb velocities. The greater flood velocities typically cause increased turbidity due to the retardation of particles settling out of the water column resulting in a landward transport due to the deformation of the tidal wave as it moves through the Greens Creek inlet (Nichols and Biggs, 1985). Light extinction through the water-column is described as the exponential decrease of light with increasing depth, characterized as the light extinction coefficient (k). Light extinction coefficients ranged from 0.74 to 3.27 throughout the study period and varied greatly among transect stations yet showed no apparent seasonal trends. The highest k values were generally associated with the mid-reaches of Greens Creek and the lowest k values generally associated closer to the mouth of the creek. These results provide evidence that the flood flows are associated with high turbidity that strongly attenuates light and possibly acts as a constraint on phytoplankton growth at stations located in the upper reaches of Greens Creek (stations 3A – reservoir).

Photosynthetically active radiation measurements at stations 5 and 3 showed the largest k variations, defined as 1% of surface light, as compared to all other stations along the transect. Station 5, located outside of Greens Creek in the Machipongo River, is the deepest of the water-column stations with a low tide depth of approximately 16 meters

and a mean photic depth of about 2 meters (+/- 0.5 m). On the other hand, station 3, located near the entrance of Greens Creek, has a shallower water-column with a low tide depth of about 2 meters and a mean photic depth of 1.3 meters (+/- 0.3 m). The mean light extinction coefficients for stations 3 and 5 are moderate values based on a survey of diverse estuaries conducted by Nixon (1986) and Mallin et al. (1991). The photic depths and *k* values determined for station 5, 3 and 3A provide evidence that flood flow into Greens Creek promotes increased turbidity in the water column. This increased turbidity results in light never being distributed homogeneously throughout the water-column or along the transect (Huisman and Weissing, 1994). In essence, this data suggests that the upper reaches of Greens Creek are characterized by an increase in suspended particulates in the water-column than the lower reaches and thus the phytoplankton populations residing in the upper reaches may be prone to light limitations.

Phytoplankton

Many studies have been conducted on phytoplankton within estuarine systems, although very few have focused on the sea-side of Virginia's Eastern Shore. Phytoplankton pigment concentrations provide a bounty of ecological information regarding the health of phytoplankton communities and provide a quantifiable method of estimating phytoplankton abundance. In addition, chlorophyll *a* concentrations in particular are also an important indicator of light availability within a system and provide a useful survey of primary production.

Day-to-day responses of phytoplankton to freshwater nutrient inputs are highly variable both temporally and spatially. Similar to the conclusions of many researchers who study temperate estuaries, the results of this research show the development of two blooms throughout the year. Chlorophyll *a* concentrations at each station throughout the study period exhibited large concentration ranges over the study period. For all sampling years of the study (1996 – 1998) maximum chlorophyll *a* concentrations occurred first during the early spring months (February) and again during the summer months (June – August). Mean chlorophyll *a* was 8.50 μg/L for all of the collected samples with a range from 0.46 to 32.84 μg/L during bloom conditions. Summer chlorophyll maximums

coincide with increased water temperatures (Fig. 20) and elevated reservoir and rainfall nitrate levels that are presumed to have stimulated the bloom. Increased biomass during bloom conditions are associated with high nitrate concentrations providing evidence of the ecological impact that freshwater sources have on the primary production occurring within the Greens Creek system (Fig. 24). These biomass estimates are very similar compared to the lower Neuse estuary in North Carolina (Table 25) where chlorophyll *a* measurements range from 2.2 to 23.0 μg/L (Mallin et al., 1991). In addition, other oligotrophic estuaries of North Carolina have been reported to range between 1.6 to 9.4 μg/L (Thayer, 1971) and the Pamlico River Estuary ranged from 0.8 to 184.2 μg/L (Stanley, 1987). In estuaries with multiple years of biomass data, mean chlorophyll *a* concentrations show an apparent response to long-term nutrient loading increases. In essence, the biomass estimates for Greens Creek are comparable with other temperate estuarine systems and shown to be highly correlated with nutrient rich freshwater sources.

TABLE 25. Chlorophyll *a* concentrations for various North Carolina estuarine systems. All data from Mallin (1991).

Location	Period	Chl-*a* Mean (μg/L)	Range
Neuse River Estuary			
Christian et al. (1991)	1985-1989	10.5	-
Mallin et al. (1991)	1988-1989	11.8	2.2 – 23.0
Mallin (1992)	1990-1991	14.3	1.6 – 64.8
Beaufort Estuary			
Thayer (1971)	1967-1968	3.8	1.6 – 9.4
Pamlico River Estuary			
Hobbie (1971)	1966-1967	10.8	1.0 – 48.0
Stanley (1987)	1986	17.3	0.8 – 184.2

In addition to phytoplankton biomass estimates, phaeophytin *a* (phaeo-a), the degraded form of chlorophyll *a* (chl-a), was measured because it serves as a useful indicator of the health of the natural algal population. In order to determine the health of the phytoplankton populations in Greens Creek, photopigment ratios ([chl-a:phaeo-a]) were calculated to estimate the percent of degraded chlorophyll cells (Table 19). The pigment composition of a population is an ideal indicator of the physical condition of the algal community. Percent degradation ranged from 32.31% to 65.97% with lower percentage values representing healthier phytoplankton cells. Conversely, higher percentages represent senescent or degrading cells. Overall, these results show that the healthiest cells are apparent during bloom conditions or periods of stimulated growth generally in the spring and later summer months while there is an increase in cell degradation during winter months when production and corresponding biomass is the lowest.

A strong relationship exists between the less than 20 μM chlorophyll size fraction and total chlorophyll (Fig. 26). Overall, the less than 20 μm size fractions comprises a significant percentage of the total measured chlorophyll at all stations over the sampling period. These results indicate that phytoplankton species less than 20 μM in size constitute on average ~91% of the total phytoplankton production occurring within Greens Creek. The significance of small phytoplankton is often overlooked in estuarine studies due to a variety of factors: sampling methodology, phytoplankton assessments rarely census the entire community and most research typically focus on pristine systems (Carrick and Schelske, 1997). It is important to measure size-fractionated chlorophyll a when investigating phytoplankton biomass since smaller species are often ruptured in the traditional preservation process. It is presumed that the difficulties in determining the abundance of small phytoplankton (<20 μM) may exacerbate the many misconceptions that increasing algal size is correlated to increased nutrient availability (Carrick and Schelske, 1997) and in turn underestimate their ecological significance in productive systems.

Three major taxonomic groups dominated the phytoplankton of Greens Creek: Dinophyceae (dinoflagellates), Bacillariophyceae (diatoms) and Cryptophyceae (cryptomonads). Diatoms and dinoflagellates tended to dominate the algal populations.

Diatoms tended to predominate during fall and spring months and dinoflagellates in winter and early summer months. Cryptomonads typically dominate during periods of decreased salinity; although, these results show a correlation with maximum nitrate concentrations (up to ~ 706 μM) entering the upper reaches of the creek at the reservoir spillway during May 1998 (Fig. 16). Species identifications of preserved cell samples revealed that the <20 μm size class was composed primarily of species such as: *Leptocylindrus minimus, Thalassionema nitzschioides, Skeletonema costatum, Cryptomonas pseudobaltica* and a variety of other small diatoms. The larger species (>20 μm) consisted of a variety of diatoms including *Coscinodiscus* spp., *Rhizosolenia setigera, Pleurosigma* spp., *Corethron criophilum* and dinoflagellates such as *Heterocapsa triquetra, Gymnodinium splendens* and *Dinophysis* spp. Cyanobacteria, or Cyanophyceae, were not investigated as part of this research since blue-green algae have a strong intolerance for salinity (Paerl et al., 1984; Sellner et al., 1988) and a strong aversion to prevalent well-mixed conditions (Paerl, 1988) typical in Greens Creek during high tides.

In order to evaluate changes in phytoplankton production it is important to investigate the corresponding grazing pressure of the zooplankton community. The development of two zooplankton blooms throughout the sampling period were apparent with maximum biomass occurring first during the late fall (November 1997) and again during the spring months (March - May). Of the two bloom events biomass estimates were greater during the spring months (March – May) with maximum cell densities occurring in March 1998 equivalent to ~10,790 cells per liter. Cell density during November 1997 only reached ~951 cells per liter. The mean phytoplankton density for Greens Creek was 9.78 ($*10^5$) cells per liter and ranged from 4.7 ($*10^4$) to 1.8 ($*10^6$) cell per liter. These algal densities are comparable to other estuaries. For instance, researchers showed that the Cape Fear estuary contained an average of 1.56 ($*10^6$) cells per liter (Carpenter, 1971) while a multi-year investigation on the Neuse River estuary yielded 2.1 ($*10^5$) to 4.24 ($*10^6$) cells per liter (Mallin et al., 1991). The cell density results of both zooplankton and phytoplankton in conjunction with regression relationships (Fig. 30) indicate that there is very little grazing pressure exerted by zooplankton on the phytoplankton population within Greens Creek. Grazing by

zooplankton only accounts for approximately 2% of the phytoplankton mortality within this system. Therefore, the consideration of a single parameter in controlling phytoplankton abundance is not satisfactory.

In addition to cell density, results of this research show that zooplankton species composition changed little from season to season. Tow samples were dominated by two copepod genera, *Acartia* and *Centropages*, and other species including fish larvae, jellyfish, juvenile welch and horseshoe crabs were found in low numbers. The fall (November 1997) bloom has less biomass than the spring (March 1998) bloom with densities equivalent to 950.97 and 10,789.76 animals per liter respectively, although the fall bloom had greater species diversity than the spring bloom.

Previous experimental studies in large-scale mesocosms has established a strong linear relationship between nutrient loading and phytoplankton biomass (Nixon and Pilson, 1983; Nixon et al., 1984; Keller, 1988). In essence, the predictive ability of a model that includes both measurements of light availability and phytoplankton biomass can aid phytoplankton research tremendously (Keller, 1988) but the model is only based on "instantaneous", depth integrated primary production. Stations 5 and 3 of the Greens Creek transect were chosen to investigate primary productivity differences that exist both outside (station 5) and inside (station 3) Greens Creek. The PAR results indicate that at low tide, phytoplankton are able to utilize the entire water-column of station 3 while production is limited to the first few meters of the water-column at station 5. Sediment exchange transported into the creek during tidal recharge may play a large role in phytoplankton dynamics at station 3 since increased tidal energy causes the resuspension of sediments that then supply available nutrients to the shallow water-column.

The model assumes that phytoplankton biomass (B), measured as chlorophyll *a*, is homogeneously distributed throughout the photic zone which is not true for deeper stations along the transect such as station 5. Generally, station 5 showed greater total chlorophyll *a* concentrations than station 3 per sampling date yet both stations showed the same apparent seasonal trends with maximum chlorophyll concentrations occurring in the early spring – summer months and minimum concentrations in the late fall – winter months. Overall, the standing crops of phytoplankton at station 5 and station 3 statistically had the same total chlorophyll *a* concentrations with mean concentrations

equal to 3.42 (+/- 2.59) and 3.07 (+/- 2.01) mg Chl-*a* m^{-3} respectively. Station 5 generally had greater daily biomass estimates that provide evidence of an upstream gradient in chl-*a* concentrations within the creek. Surface irradiance values were generally greatest during the summer months and lowest during the winter months, as one would expect due to changes in sun angle and intensity over the year.

The model data presented here suggests that annual production values are highly variable due to variations in light but also due to daily variations in biomass and photic depths compounded on an annual cycle. These results show the apparent danger of estimating annual productivity from single locations within an estuarine system since phytoplankton productivity can vary significantly along even small spatial gradients. Model derived annual productivity was estimated to be 62.54 and 37.14 g C m^{-2} $year^{-1}$ for station 5 and 3 respectively with both stations showing the same seasonal trends with maximum chlorophyll specific production occurring in early spring months for years 1997 and 1998. Minimum production occurred in the late fall months corresponding to the time of year when total chlorophyll *a* concentrations and surface irradiance measurements are at a minimum.

Station 5 statistically exhibited the same modeled daily productivity as station 3 with mean values of 171.35 and 101.76 mg C m^{-2} day^{-1} respectively. However, the annual modeled results based on the daily-derived productivity values varied significantly with values ranging from 8.64 to 222.49 g C m^{-2} $year^{-1}$ at station 5 and 3.17 to 134.42 g C m^{-2} $year^{-1}$ at station 3. Production varied seasonally both within and outside of Greens Creek. The principal obstacle encountered with both the model and mesocosm experiments is having to interpolate daily (or 24 hour) production based on instantaneous surface irradiance measurements or incubations which only lasts a few hours, as well as the added pitfall in extrapolating annual production from daily estimates. The low production estimates determined using the model is evidence of this fact.

Model production estimates determined for Greens Creek in this research are quite low as compared to the annual primary production estimates (Table 26). Of the selected systems, the Pamlico River estuary has the highest annual primary productivity of 500 g C m^{-2} $year^{-1}$ (Kuenzler et al., 1979) as compared to other systems (Table 26). Conversely, an investigation on Beaufort area estuaries showed that these systems have

an annual primary productivity equal to 66.6 g C m^{-2} $year^{-1}$ (Thayer, 1971). Modeled annual productivity at station 5 and station 3 of the Greens Creek transect equated to 62.54 g C m^{-2} $year^{-1}$ and 37.14 g C m^{-2} $year^{-1}$ respectively. Under ideal culture conditions, phytoplankton productivity has been estimated on a variety of occasions for Greens Creek with results ranging from 110 – 170 g C m^{-2} yr^{-1} (Dunstan, personal communication) at least a two-fold increase over model derived production estimates. The model and measured data presented in this research provides evidence that further downstream of the turbidity maximum where the water has cleared, light limitations are alleviated allowing increased phytoplankton abundance and productivity (Cloern et al., 1983, Harding et al., 1986, Fisher et al., 1988).

TABLE 26. Annual primary productivity (P_{year}) expressed as g C m^{-2} $year^{-1}$ for several selected estuarine and coastal systems.

Site	P_{year}	Reference
Narragansett Bay		
Mid-Bay	308	Furnas et al. (1976)
GSO Dock	189	Keller (1988)
Hudson Bay		
Bight	370	Malone (1976)
Lower Bay	200	Malone (1976)
Chesapeake Bay		
Mid-Bay	335 – 780	Boyton et al. (1982)
Beaufort area estuaries	66.6	Thayer (1971)
Neuse River estuary	342.6	Mallin et al. (1991)
Pamlico River estuary	500	Kuenzler et al. (1979)
Delaware Bay	190 – 400	Pennock and Sharp (1986)
San Francisco Bay	95 – 150	Cole and Cloern (1984)

Since day-to-day responses of phytoplankton to freshwater nutrient inputs are highly variable the results obtained from the use of a model such as this as a predictive tool for estimating primary productivity can often be misleading. Model results should be viewed cautiously. The principal problem encountered with model experiments is having to interpolate daily production based on instantaneous light measurements which add to the difficulty in interpolating annual production from daily estimates. The factors employed in the model result in instantaneous, depth integrated primary production based on continually changing parameters such as phytoplankton abundance, depth of the photic zone and the amount of incident light. The model data presented here not only suggests annual production values are highly susceptible to temporal variability but also to daily fluctuations in biomass and photic depths. In addition, these results also show the danger in estimating annual productivity from single locations within an estuary since phytoplankton productivity can vary significantly along even small spatial gradients.

Greens Creek Water Quality

A model of estuarine nutrient fluxes through Greens Creek over a two year period demonstrates that this estuary has indeed a series of complex biogeochemical interactions. The interplay of tidal forces, light and nutrients in regulating phytoplankton populations in Greens Creek arises from the dominant seasonal variations in freshwater discharge and the corresponding nutrient composition of that flow. Freshwater discharge from the reservoir spillway contributes nutrients, particularly N, P, and silica available for phytoplankton uptake. The relationship between nutrient loading and phytoplankton uptake is controlled in part by the observed nutrient distributions and the dynamic salinity conditions in the creek. Furthermore, on a larger scale the extent to which nutrients are exported to the neighboring coastal lagoon depends primarily on how the quantity and nature of the nutrients are modified as they are transported through the creek.

The data from this research concludes that there are no strong relationships between nitrate, phosphate, silicate and total chlorophyll *a* as compared to surface salinity. Nitrate concentrations exhibited the strongest correlation ($r^2 = 0.351$) with salinity as compared to all other measured parameters. Despite this result the nitrate -

salinity correlation is still an extremely weak relationship. Similar to the regression equation determined for nitrate, the regression value equated for phosphate concentrations also showed only a marginal correlation with salinity ($r^2 = 0.184$). Conversely, the regression values for both silicate and total chlorophyll *a* show no relationship with salinity. Regression values were equated to be $r^2 = 0.003$ and $r^2 = 0.006$ for silicate and total chl-*a* respectively. These results provide evidence that local processes within the water column of Greens Creek dominantly control the available nutrient concentrations of nitrate, phosphate, silicate and total chlorophyll *a*. In order to understand the distributions of phytoplankton nutrients within the Greens Creek system and attempt to determine the fates of these freshwater inputs mixing diagrams were created.

This research produced thirteen months of nutrient profiles in order to understand the impact that the continuous flux of freshwater discharge (i.e. groundwater and reservoir discharge) and additional direct and indirect inputs by episodic rainfall events have on this marine system. These nutrient profiles serve as an aid to better understand the behavior of freshwater borne nutrients within the marine water-column as well as those processes that regulate the input, removal and recycling of these nutrients within Greens Creek. The results of the profiles suggest that biogeochemical processes control the observed nutrient concentrations along the Greens Creek transect rather than the mere physical mixing processes of fresh and seawater. The distribution of all measured nutrient species showed concentration fluctuations along the Greens Creek transect on all sampling dates. In general, the details of the NO_3^-, NH_4^+, PO_4^{3-} and SiO_2 nutrient profiles show that over an annual cycle, there are generally only two patterns of nutrient distribution for each measured nutrient.

The distributions of nitrogen within marine systems have been an important issue for many years since N is both critical for algal growth and an extremely important factor in nutrient loading management issues (Ryther and Dunstan, 1971). Overall, all measured N fractions showed large temporal and spatial fluctuations over the sampling period with NO_3^- concentrations representing the greatest total concentration of N (78%). However, NO_3^- also showed the greatest variation in concentrations compared to both NH_4^+ and NO_2^- with concentrations ranging from nearly 0 to ~706 μM along the entire

transect. More specifically, freshwater nitrate concentrations at the reservoir spillway ranged from roughly 60 μM to as high as 706 μM. In all instances, NO_3^- concentrations decreased non-linearly as salinity increased with NO_3^- concentrations in the lower reaches significantly lower than those measured in the upper reaches (Valiela, 1984; Comin and Valiela, 1993). At higher salinities, nitrate decreased rapidly near the seaward edge of the transect indicative of nitrate uptake in the water-column by phytoplankton is an important removal mechanism (Fisher et al., 1988, Jordon et al., 1991). Nitrate concentrations remained low at the seaward end (station 5) with concentrations typically less than 5 μM. These nitrate profiles conclude that a large percentage (~90 – 98%) of the total nitrate imported to the creek via freshwater sources is removed due to local processes.

Nitrate addition curves are evident on several sampling occasions (August, October, February – April) in the lower saline waters of the creek indicative of a prominent nitrate source. The primary nitrate source to Greens Creek is discharge through the reservoir spillway as compared to sub-surface groundwater and rainfall events. Although slight nitrification may serve as a secondary source of nitrate input in salinity typically less than 15.

Nitrite concentrations were consistently the most negligible DIN species accounting for only 5% of the total DIN for all sampling events. Although nitrite profiles are not shown it still serves as an important N species within the creek. Nitrite concentrations typically decreased non-conservatively with increasing salinity suggesting a nitrite sink, such as nitrification, in the mid- to lower reaches of the transect.

Ammonium was a moderate component (22%) of the total dissolved inorganic nitrogen pool within the creek. Ammonium concentrations showed slight seasonal variation over the sampling period with concentrations being significantly smaller than those previously described for nitrate. Ammonium concentrations ranged from 0.2 to 7.7 μM with maximum concentration generally occurring within the mid-reaches of Greens Creek. Ammonium concentrations tend to show NH_4^+ production in the upper to mid-reaches of the transect (reservoir spillway to station 3B) with consumption occurring in the lower more saline reaches (stations 3 – 5) similar to the results of the nitrate profiles. There are some exceptions to this trend in which NH_4^+ concentrations increased along the

entire length of the transect but a seasonal trend is difficult to decipher. These profiles render confirmation that a significant contribution (~1 μM) of ammonium is supplied to the upper reaches of the Greens Creek water column throughout most of the year. The distribution of ammonium along the Greens Creek transect was non-conservative because of the combined influence of riverine inputs, phytoplankton uptake and water-column denitrification. In general, the non-conservative NH_4^+ behavior indicates either an external input of ammonium along the transect (i.e. sub-surface shallow groundwater) or the reduction of NO_3^- to NH_4^+ due to denitrification processes at work in the water-column. In addition, NH_4^+ is being consumed speculatively by biological phytoplankton uptake in the lower reaches of the transect.

In addition to dissolved inorganic nitrogen, dissolved reactive phosphate is also a key component for phytoplankton growth and production. Concentrations of PO_4^{3-} display great temporal and spatial variability on all sampling dates with concentrations generally ranging between 0 – 8 μM although concentrations as high as ~16 μM were evident in the mid-reaches of the creek on February 7, 1998. Unlike the results described for nitrate and ammonium, phosphate profiles show appreciable additions to the water-column occurring along the entire length of the transect with concentrations increasing with salinity from the upper to lower reaches of the creek. It is speculated that riverine particulate reactive phosphate dissolves or is regenerated after deposition into the creek's sediments rather than in the water-column, and therefore augments the dissolved reactive phosphate regeneration input signal along the length of the creek (Fisher et al., 1988). Particulate reactive phosphate was not measured as part of this research thereby making conclusions regarding dissolved inorganic phosphate somewhat difficult. The pattern of PO_4^{3-} input along the transect is altered in the mid- to late summer months when slight removal occurs in the upper to mid- reaches of Greens Creek. Observed P-removal occurred in the freshwater reaches of the transect and is attributed to the adsorption of reactive phosphate with organic matter and uptake by phytoplankton. A third phosphate pattern is visible in which PO_4^{3-} is added to the creek water column from the reservoir spillway to station 3A with removal occurring from station 3A to the end of the transect at station 5. This third PO_4^{3-} pattern, unlike all other profiled nutrients, was apparent on January 7, 1997 and September 25, 1997 therefore by disregarding a temporal influence.

This pattern suggests that phosphate regeneration due to the desorption of reactive dissolved phosphate from sediments is occurring in the freshwater reaches while phytoplankton uptake is removing PO_4^{3-} in the higher salinity reaches. Throughout this research phosphate exhibits non-linear behavior with freshwater concentrations being less than the concentrations in the more saline waters of the transect. The non-conservative behavior provides evidence of PO_4^{3-} being released from riverine particulate matter and taken up by phytoplankton for growth rather than solely the mixing of P-limited freshwater and P-rich marine water.

The distribution of silicate was very non-conservative, indicating biological uptake and geochemical dissolution processes control concentrations within the Greens Creek system. Dissolved silica is an effective indication of the reactive effects of freshwater inputs and phytoplankton productivity especially in areas where diatoms are a large component of the phytoplankton population. Maximum silicate concentrations were generally found at the freshwater endmember of Greens Creek with concentrations decreasing toward the saline endmember. Water-column SiO_2 concentrations increased during the late summer and early fall months suggesting a correlation with increased water temperatures which promote regeneration of silicate either from the water-column or sediments. Silicate concentrations show prominent signs of input throughout the course of the study primarily due to freshwater sources and regeneration processes. Even though, intermittent periods of removal did occur in the more saline reaches (stations 3 – 5) of the transect it is difficult to decipher any seasonal removal trends.

The distribution of dissolved inorganic nitrogen, phosphorus and silicate have been presented for the Greens Creek system, and an attempt has been made to determine the fates of freshwater inputs of these nutrients using mixing diagrams (Sholkovitz, 1976; Peterson et al., 1985; Fisher et al., 1988). In Greens Creek, the results suggest that nitrate, ammonium, phosphate and silicate concentrations exhibited non-linear, or non-conservative, behavior concluding that measured concentrations are indeed controlled by local processes occurring within the system more so than by ambient nutrient-salinity relationships (Fisher et al., 1988). The inputs of nitrate, ammonium, phosphate and silicate were removed as phytoplankton biomass (Fisher et al., 1992) accumulated in the lower reaches of the transect, whereas nitrite removal was influenced more by

nitrification. Freshwater nutrient inputs via reservoir discharge, groundwater and precipitation events are vital for this estuarine system. These nutrient rich freshwater sources provide the necessary nutrients needed for phytoplankton growth. Evidence presented in this research suggests that most of the primary production within this system occurs in the lower reaches of the Greens Creek transect corresponding to the higher salinity waters due to the alleviation of light limitations (Fisher et al., 1988, Pennock and Sharp, 1994).

CONCLUSIONS

The focus of this research is to determine if an increase in external nutrient loading into Greens Creek will not result in a subsequent increase in primary production due to a combination of intense light limitations and high tidal exchange rates in this creek system. This research identified the many biogeochemical and physical interactions within the Greens Creek water-column needed to understand the importance of freshwater sources in governing phytoplankton production. On an annual basis, the continuous freshwater discharge from the reservoir spillway accounts for a large percentage (>99%) of the total freshwater nutrient inputs deposited directly into Greens Creek. Groundwater discharge and atmospheric deposition provide an important secondary source of nutrients to this system, although only a small percentage (<1.0%) with both direct and indirect rainfall events being of substantial significance on shorter time scales. This research provides evidence that small freshwater creeks have a considerable influence on the nutrient dynamics occurring within this estuarine system and consequently have a large ecological significance in governing primary production.

The results of the primary production model and an average photic depth of 1.6m determined from the water-column light profiles used in this research have shown that phytoplankton utilize 1.8 ($*10^{4}$) g C m^{-2} $year^{-1}$ in Greens Creek. Based on the Redfield ratio of C:N:P (106:16:1), phytoplankton require 169.7 g N m^{-2} yr^{-1} and 10.6 g P m^{-2} yr^{-1}. According to the nutrient data determined from this research, freshwater nutrient sources contribute a total of 4.98 ($*10^{8}$) g DIN m^{-2} $year^{-1}$ and 1.67($*10^{4}$) g P m^{-2} $year^{-1}$. This means a difference of 4.97($*10^{8}$) g N m^{-2} $year^{-1}$ and 1.67($*10^{4}$) g P m^{-2} $year^{-1}$ are not being utilized by phytoplankton in this system. Assuming that microbial and sedimentary processes are also consuming a portion of this available N and P equal to that of phytoplankton, there would still be an appreciable amount of N and P available in Greens Creek. This example provides evidence that freshwater nutrient input to Greens Creek are not being fully utilized and thus are available to be exported out of the system. These results further indicate that some factor other than nutrient supply is limiting phytoplankton production in this estuarine system.

Tidal flushing and nutrient property-property plots provide additional evidence that phytoplankton in Greens Creek are light-limited in the turbid nutrient-rich waters of the upper and mid-reaches of the creek. However, as water becomes clearer downstream in the lower more saline reaches, light becomes more available, phytoplankton production increases and nutrients are utilized. Evidence of nutrients as the limiting factor in phytoplankton growth was not detected; although, limitations may occur in the more clear lower reaches of the transect (station 4 – 5) but recharging tides characterized by high tidal energy break down the freshwater stratification and create a well-mixed water-column. This well-mixed environment drastically decreases freshwater nutrient concentrations due to increased dilution thus limiting phytoplankton growth. Daily phytoplankton production was strongly correlated with ambient nitrate concentrations (Fig. 24) and inversely correlated with salinity (Fig. 33d), emphasizing the importance of freshwater input as a nutrient-loading source. The key to phytoplankton growth in the Greens Creek estuarine system is a stable stratified water-column.

In addition, it appears that in the upper freshwater reaches of Greens Creek that N is in abundance and biologically available for phytoplankton uptake yet growth is light-limited. Although the relationship of freshwater flow to the accumulation of phytoplankton biomass in this system is complex, this research suggests that Greens Creek is capable of assimilating further nutrient inputs and produce even larger phytoplankton standing crops with increased light availability. However, caution must be taken since increases in nutrient supply with the proper light conditions may result in the enhancement of primary production and biomass within Greens Creek. Secondary effects which may result in changes in the plankton community structure and possibly favor toxic bloom species. Thus control of nutrient inputs from freshwater sources is an important management issue for the Greens Creek and surrounding watersheds.

On an annual basis, Greens Creek receives a total of $1.80(*10^7)$ moles DIN $year^{-1}$ and $1.72(*10^5)$ moles P $year^{-1}$ through rainfall events, groundwater and reservoir discharge which on a per volume basis is greater than the total N and P that other larger estuarine systems receive via freshwater sources. The results of this research have deduced several conclusions:

1.) It is often difficult to compare freshwater nutrient imports to estuarine systems since watersheds are typically so large that estimates are based on conservative regional determinations not actual measurements.

2.) The ability of these systems to retain the available N and P imported to them via freshwater sources is largely a function of flushing rate of that system.

3.) Sampling protocol is extremely important since physical and biogeochemical processes act quickly on freshwater entering a system; therefore, samples must be derived from the freshwater sources themselves in addition to further downstream.

4.) Finally, most estuarine systems only consider large rivers as the primary sources of freshwater nutrients to a system and often the contributions by small streams and tidal creeks are overlooked.

More importantly, the information gained in this research has far greater applications than merely a single site. The Greens Creek nutrient distributions and subsequent phytoplankton production may be representative of other estuarine systems on the Eastern Shore of Virginia. In Northampton County (Virginia) alone there are eight named creeks and 13 un-named creeks similar to Greens Creek flowing into the Eastern Shore's coastal lagoon system. Moreover, the extent to which nutrients are exported to the coastal lagoon depends on how the quantity and nature of the nutrients are modified within these creek systems; therefore, it is important to understand the role that these small freshwater creeks have in influencing coastal systems. Additional research on the extent to which nutrient inputs in excess of those needed by phytoplankton should be conducted to determine the importance of these freshwater nutrient sources in regulating coastal primary production.

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APPENDIX A.1

EASTERN SHORE PRECIPITATION NUTRIENT DATA

DATE	RAINFALL (inches)	Vol. Weighted NH4	Vol. Weighted NO3	Vol. Weighted NO2	TOTAL DIN (µmol/L)	Volume Weighted DON	TOTAL N Volume Weighted	Vol. Weighted PO4
8-Oct-96	3.91	4.50	6.14	0.86	2.94	-	-	2.54
9-Oct-96	0.15	0.10	0.16	0.10	2.36	-	-	0.10
28-Jan-97	0.55	2.55	9.42	0.02	21.80	53.18	65.17	1.67
2-Feb-97	0.82	6.05	74.25	0.38	98.38	-	-	2.94
8-Feb-97	0.70	3.11	24.79	2.04	42.76	-	-	1.89
14-Feb-97	0.80	7.20	43.01	2.85	66.32	-	-	8.66
15-Feb-97	0.62	1.69	6.86	1.17	15.69	27.76	37.49	1.74
28-Feb-97	0.54	2.87	10.91	0.28	26.04	-	-	2.11
4-Mar-97	0.25	1.50	2.19	0.16	15.40	16.58	20.43	0.65
10-Mar-97	0.24	1.60	19.47	0.17	88.51	-	-	0.97
14-Mar-97	0.30	0.87	11.06	0.21	40.47	-	-	0.63
19-Mar-97	0.72	1.67	10.43	0.03	16.84	-	-	1.89
26-Mar-97	0.73	2.43	23.93	0.26	36.47	79.90	106.52	1.57
31-Mar-97	0.28	1.94	14.48	0.15	59.18	-	-	0.94
13-Apr-97	0.42	2.31	9.27	0.21	28.05	-	-	1.13
23-Apr-97	0.17	0.53	2.45	0.68	21.48	-	-	0.16
28-Apr-97 (am)	0.40	2.57	23.99	0.33	67.23	16.21	43.10	1.00
28-Apr-97 (pm)	0.41	1.18	5.66	0.25	17.28	-	-	0.88
29-Apr-97	0.67	1.62	13.27	0.23	22.57	-	-	1.76

APPENDIX A.1 continued.

14-Jun-97 (am)	1.38	37.91	126.61	0.26	119.41	292.33	457.11	8.45
23-Jun-97 (am)	0.39	39.99	8.97	0.46	126.71	-	-	28.93
25-Jul-97 (am)	3.51	128.87	68.21	1.34	56.53	769.01	967.42	25.84
25-Jul-97 (pm)	0.42	19.15	14.88	0.19	81.49	-	-	9.97
5-Aug-97	1.26	54.74	30.77	0.16	67.99	223.84	309.51	27.46
21-Aug-97	0.48	22.97	6.99	0.28	63.01	-	-	1.08
28-Sep-97	0.48	2.63	7.97	0.20	22.50	32.59	43.39	0.00
18-Oct-97	1.29	6.86	14.99	0.47	17.30	-	-	0.00
19-Oct-97	0.76	5.20	6.85	0.16	16.06	20.92	33.12	0.00
26-Oct-97	0.49	3.57	14.67	0.10	37.45	-	-	5.94
1-Nov-97	1.46	6.67	13.87	1.42	15.04	-	-	0.00
7-Nov-97 (am)	0.91	5.87	13.72	0.21	21.77	-	-	21.29
7-Nov-97 (pm)	0.08	0.27	0.50	0.01	9.70	-	-	0.54
9-Nov-97	1.00	3.03	10.67	0.52	14.21	27.27	41.48	0.96
13&14-Nov-97	0.28	1.99	25.01	0.06	96.61	-	-	0.37
22-Nov-97	0.49	13.74	138.45	0.22	311.03	-	-	1.62
30-Nov-97	0.48	16.04	28.39	0.04	92.65	-	-	2.94
4-Dec-97	0.32	5.60	79.47	0.03	265.95	-	-	0.98
27-Dec-97	0.61	11.39	67.38	0.26	129.55	-	-	2.71
12-Jan-98	0.50	12.29	122.18	0.23	269.42	-	-	1.32
15-Jan-98	0.55	3.15	45.64	0.12	88.94	-	-	1.20

APPENDIX A.1 continued.

16-Jan-98	0.55	3.55	20.53	0.57	44.84	-	-	1.34
17-Jan-98	0.23	1.97	31.51	0.33	147.02	18.73	52.55	0.41
23-Jan-98 (AM)	0.54	3.24	132.95	0.08	252.35	76.74	213.01	1.04
23-Jan-98 (PM)	0.44	3.00	41.64	0.21	101.91	-	-	0.90
28-Jan-98 (AM)	2.71	4.71	82.94	0.63	32.58	-	-	4.45
28-Jan-98 (PM)	0.65	1.19	12.72	0.14	21.62	-	-	0.92
3-Feb-98 (ON)	0.61	3.72	127.87	0.09	215.87	-	-	0.72
5-Feb-98 (DAY)	1.34	2.46	47.40	0.26	37.40	-	-	1.91
5-Feb-98 (ON)	1.53	1.93	62.30	0.65	42.40	-	-	2.23
12-Feb-98 (ON)	0.50	3.54	46.47	0.14	100.29	-	-	0.50
17-Feb-98 (PM)	1.03	4.03	89.49	0.29	91.07	436.26	530.06	1.17
23-Feb-98 (PM)	1.34	8.66	80.29	0.14	66.49	-	-	3.78
8-Mar-98 (PM)	0.05	0.26	2.84	0.01	62.36	2.08	5.20	0.06
9-Mar-98 (AM)	1.23	3.08	47.40	0.24	41.23	-	-	1.69
18-Mar-98 (DAY)	1.91	5.41	73.60	0.37	41.56	-	-	2.60
18-Mar-98 (ON)	0.20	0.52	16.23	0.04	83.94	-	-	0.24
21-Mar-98 (ON)	0.73	1.23	30.45	0.12	43.56	-	-	0.76
4-Apr-98 (PM)	0.65	5.07	52.77	0.11	89.16	74.13	132.09	1.70
1-May-98	0.67	5.26	40.99	0.11	69.20	-	-	1.37
5-May-98 (ON)	0.52	7.31	65.25	0.20	139.94	-	-	0.95
8-May-98 (AM)	0.46	7.12	104.25	0.13	242.37	22.03	133.52	0.60

APPENDIX A.1 continued.

8-May-98 (PM)	0.76	4.72	105.87	0.16	145.73	-	-	1.26
13-May-98 (ON)	0.74	4.31	12.38	0.11	22.70	-	-	1.70
16-May-98	0.42	17.21	195.82	0.18	507.66	-	-	68.66
27-May-98 (pm)	0.67	11.85	51.01	2.83	98.05	-	-	66.79
10-Jun-98	0.57	21.26	213.36	5.06	420.48	105.07	344.75	40.90
14-Jun-98 (am)	0.70	25.89	83.72	0.59	157.43	-	-	131.35
15-Jun-98 (pm)	0.60	11.21	67.83	6.08	141.87	-	-	29.54
24-Jun-98 (pm)	0.45	11.83	103.21	5.32	267.47	1129.01	1249.38	166.80
27-Jun-98 (on)	0.25	8.25	61.96	6.02	304.90	867.32	943.54	109.97
28-Jun-98 (am)	0.60	21.22	74.60	0.51	160.55	274.24	370.57	103.83
29-Jun-98	0.66	26.95	90.13	1.12	179.08			121.65
5-Jul-98 (am)	1.50	46.95	366.37	4.44	278.50	825.96	1243.71	427.80
TOTAL (n= 73)	55.63	737.13	3794.08	54.40	7264.67	5391.16	7343.12	1474.42
Average Rainfall	0.76							
Average Concentration (µM)					99.52			
Volume Weighted Average (µM)		10.10	51.97	0.75		245.05	333.78	20.20
Vol. Weighted Std. Deviation		17.84	59.17	1.39		339.22	404.28	59.02
Volume Weighted Average (mg/L)		181.76	3222.37	34.28		3920.84		1918.77

APPENDIX A.2
PRECIPITATION FORMULAS

$\mu g\ L^{-1}$ of nutrient species = μM * atomic weight

$mg\ m^{-3}$ of nutrient species = $\mu g\ L^{-1}$ of nutrient species * ($1000L\ m^{-3}$) = $1000\ \mu g\ m^{-3}$

Average Rainfall Flux ($mg\ m^{-2}\ event^{-1}$) = ($mg\ m^{-3}$ of nutrient * rainfall rate ($m^3\ event^{-1}$)) / watershed area (m^2)

Yearly Rainfall Flux ($mg\ m^{-2}\ year^{-1}$) = ($mg\ m^{-3}$ of nutrient * rainfall rate ($m^3\ year^{-1}$)) / watershed area (m^2)

APPENDIX A.3

TOTAL PRECIPITATION EVENTS

Event Month	Sum of Rainfall Events	Number of Storms	Average Rain Event (inches)
Oct-96	6.02	7	0.86
Nov-96	3.22	9	0.36
Dec-96	5.25	17	0.31
Jan-97	2.22	7	0.32
Feb-97	3.83	8	0.48
Mar-97	3.23	11	0.29
Apr-97	2.96	12	0.25
May-97	1.8	10	0.18
Jun-97	1.83	5	0.37
Jul-97	5.02	8	0.63
Aug-97	1.96	5	0.39
Sep-97	1.19	8	0.15
Oct-97	3.83	12	0.32
Nov-97	6.1	13	0.47
Dec-97	3.02	13	0.23
Jan-98	6.83	12	0.57
Feb-98	7.2	10	0.72
Mar-98	5.04	12	0.42
Apr-98	2.18	14	0.16
May-98	5.27	15	0.35
Jun-98	4.61	12	0.38
Jul-98	2.54	8	0.32
TOTAL	**85.15**	**228**	**8.52**
MEAN	**3.87**	**10.36**	**0.39**
STD. DEV.	**1.77**	**3.17**	**0.18**

APPENDIX A.4

WATERSHED PRECIPITATION MODEL

GRID NO.	PERCENT COVERAGE (%)	AREA OF GRID (SQ. M)
1	39	145080
2	56	208320
3	21	78120
4	76	282720
5	100	372000
6	93	345960
7	79	293880
8	100	372000
9	100	372000
10	32	119040
11	54	200880
12	100	372000
13	100	372000
14	97	360840
15	20	74400
16	6	22320
17	83	308760
18	100	372000
19	100	372000
20	29	107880
21	16	59520
22	100	372000
23	87	323640
24	2	7440
25	97	360840
26	99	368280

APPENIDX A.4 continued.

27	65	241800
28	83	308760
29	98	364560
30	98	364560
31	49	182280
32	6	22320
33	2	7440
TOTAL WATERSHED AREA =		**8135640 square meters**

APPENDIX B.1

EASTERN SHORE SHALLOW GROUNDWATER CONCENTRATION DATA

AMMONIUM				NITRATE			NITRITE			PHOSPHATE			TOTAL DIN
Date	Beach	Central	Inland	Beach	Central	Inland	Beach	Central	Inland	Beach	Central	Inland	
Feb	1.10	0.00	1.18	0.34	0.00	0.00	0.28	0.00	0.44	0.11	0.00	0.03	3.34
Mar	0.81	0.00	1.40	0.90	0.00	0.49	0.89	0.00	0.49	0.14	0.00	0.05	4.99
Apr	5.97	0.00	10.21	4.37	0.00	1.29	0.41	0.00	0.25	0.18	0.00	0.02	22.49
May	15.97	26.93	17.92	0.39	0.06	0.00	2.08	1.15	1.02	0.17	0.09	0.03	65.51
Jun	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul	3.30	2.62	3.78	0.59	0.17	0.00	0.60	0.57	0.65	0.15	0.14	0.19	12.29
Aug	2.25	2.19	2.26	8.03	1.19	0.20	0.74	0.58	0.47	0.20	0.20	0.19	17.91
Sep	4.18	3.30	2.43	1.07	1.53	0.20	0.38	0.22	0.98	0.15	0.16	0.15	14.30
Oct	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov	2.31	2.91	1.45	1.57	1.50	1.09	0.16	0.26	0.37	0.15	0.15	0.13	11.62
Dec	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jan	1.35	0.61	1.11	0.00	1.51	0.00	0.65	0.49	1.37	0.13	0.10	0.05	7.10
Feb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apr	4.03	0.75	0.81	4.98	1.52	0.00	0.28	0.56	0.65	0.05	0.04	0.05	13.57
May	1.48	1.29	0.78	0.05	0.51	1.76	0.96	0.90	0.78	0.75	0.06	0.06	8.50
Jun	13.63	1.71	2.50	0.66	1.19	0.94	0.25	0.23	0.18	0.86	0.80	0.75	21.29
Jul	4.50	1.71	2.90	0.12	3.33	1.07	0.61	0.13	0.25	0.88	0.84	0.76	14.62
Aug	4.61	2.77	3.90	0.33	2.39	0.90	0.82	0.65	0.74	0.82	0.71	0.72	17.11
Sep	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oct	2.86	3.76	3.70	1.28	8.84	2.57	2.64	2.61	0.88	4.35	3.76	5.23	29.14

APPENDIX B.1 continued.

Nov	3.89	2.56	0.92	1.46	4.36	4.51	1.57	0.46	0.77	3.05	3.22	2.95	20.49
Dec	3.99	2.84	2.77	0.09	0.76	1.35	1.62	1.58	1.58	3.25	3.05	2.81	16.56
Jan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb	2.35	3.25	3.33	3.50	5.76	3.23	0.56	0.70	2.24	2.93	3.01	2.90	24.94
Mar	3.33	1.97	4.77	9.20	70.85	9.71	0.68	0.93	0.70	2.95	3.01	2.57	102.14
Apr	2.87	3.72	2.75	13.73	16.15	6.49	0.94	1.87	1.11	2.72	2.36	2.02	49.64
May	3.19	2.31	3.33	6.06	44.27	16.19	0.32	0.26	0.49	2.06	1.54	2.00	76.42
MIN	0.81	0.00	0.78	0.05	0.06	0.00	0.16	0.13	0.18	0.16	0.13	0.18	3.34
MAX	15.97	26.93	17.92	13.73	70.85	16.19	2.64	2.61	2.24	2.64	2.61	2.24	102.14
MEAN	4.00	3.05	3.37	2.67	7.54	2.36	0.79	0.64	0.74	1.18	1.06	1.08	25.18

APPENDIX C.1

EASTERN SHORE RESERVOIR NUTRIENT DATA

Date	NH4			PO4			NO2			NO3		
	µM	Mean	Std. Err.	µM	Mean	Std. Err.	µM	Mean	Std. Err.	µM	Mean	Std. Err.
7-Aug-96	3.153	3.290	0.137	0.881	0.886	0.005	0.528	0.538	0.010	39.425	39.462	0.037
	3.427			0.891			0.548			39.500		
7-Oct-96	3.896	4.129	0.233	0.310	0.310	0.000	0.525	0.525	0.000	88.638	94.829	6.192
	4.362			0.310			0.525			101.021		
21-Nov-96	3.524	3.359	0.164	0.258	0.232	0.026	0.406	0.406	0.000			
	3.195			0.206			0.406					
7-Jan-97	1.088	0.907	0.181	0.100	0.125	0.025	1.557	1.557	0.000	80.877	80.877	0.000
	0.726			0.150			1.557			80.877		
19-Feb-97	0.705	0.694	0.011	0.200	0.200	0.000	0.232	0.232	0.000	60.229	60.229	0.000
	0.684			0.200			0.232			60.229		
16-Apr-97	0.471	0.513	0.043	0.100	0.100	0.000	0.793	0.793	0.000	100.827	100.827	0.000
	0.556			0.100			0.793			100.827		
13-May-97	1.770	1.747	0.022	0.839	0.839	0.000	0.568	0.568	0.000	112.862	111.953	0.909
	1.725			0.839			0.568			111.044		
30-Jun-97	1.478	1.422	0.056	0.791	0.791	0.000	0.465	0.465	0.000	142.820	142.865	0.045
	1.366			0.791			0.465			142.911		
14-Jul-97	1.322	1.322	0.000	0.742	0.742	0.000	0.465	0.455	0.010	133.547	133.516	0.031
	1.322			0.742			0.445			133.484		
24-Aug-97	2.464	2.464	0.000	0.791	0.791	0.000	0.588	0.599	0.010	155.743	155.729	0.014
	2.464			0.791			0.609			155.715		

APPENDIX C.1 continued.

25-Sep-97	6.238	6.238	0.000		0.041	0.041	0.000		1.791	1.791	0.000		129.798	129.892	0.094
	6.238				0.041				1.791				129.986		
23-Oct-97	4.141	4.141	0.000		3.713	3.713	0.000		0.538	0.538	0.000		128.207	128.239	0.031
	4.141				3.713				0.538				128.270		
12-Nov-97	0.722	0.722	0.000		3.363	3.363	0.000		0.767	0.767	0.000		70.870	70.793	0.077
	0.722				3.363				0.767				70.716		
9-Dec-97	0.818	0.818	0.000		2.846	2.846	0.000		0.362	0.362	0.000		79.580	79.561	0.019
	0.818				2.846				0.362				79.541		
7-Feb-98	0.549	0.549	0.000		1.380	1.380	0.000		0.320	0.320	0.000		147.116	147.116	0.000
	0.549				1.380				0.320				147.116		
22-Mar-98	1.068	1.068	0.000		1.643	1.643	0.000		0.490	0.490	0.000		204.876	204.876	0.000
	1.068				1.643				0.490				204.876		
21-Apr-98	0.780	0.780	0.000		1.982	1.982	0.000		0.383	0.383	0.000		477.592	477.592	0.000
	0.780				1.982				0.383				477.592		
23-May-98	1.336	1.336	0.000		2.517	2.517	0.000		0.469	0.469	0.000		706.472	706.209	0.263
	1.336				2.517				0.469				705.946		

APPENDIX C.2

RESERVOIR NUTRIENT DISCHARGE CALCULATIONS

AREA OF THE RESERVOIR SPILLWAY = 2[LENGTH + WIDTH] **LENGTH = 101.60 CM**

Width = 3.81 cm

Area of spillway = 210.82 cm^2 = 2.12 m^2

Volume of reservoir spillway = area * water height = (2.12 m^2)*(0.03 m)

= 0.06 m^3

Freshwater Discharge from spillway = velocity * area of spillway

= 1.60 m s^{-1} * 2.12 m^2 = 3.31 m^3 s^{-1}

Velocity measurements were made using a hand-held current meter and values ranged from 1.49 - 1.70 m s^{-1}. Mean velocity over the spillway equals 1.60 m s^{-1}.

APPENDIX D.1

TEMPERATURE AND SALINITY DATA

Date 9 MAY 1996			Date 15 JULY 1996			Date 7 AUGUST 1996			Date 22 OCTOBER 1996		
Station	Surface Temp (C)	Surface Salinity	Station	Surface Temp (C)	Surface Salinity	Station	Surface Temp (C)	Surface Salinity	Station	Surface Temp (C)	Surface Salinity
5	16.9	30.2	5	25.8	26.3	5	27	24.7	5	15.8	25.9
4	16.9	30.1	4	26.1	24.3	4	26.8	23.4	4	15.9	25.4
3	16.8	28.9	3	26.6	22.1	3	26.6	21.2	3	16	25
3A	17.1	28	3A	26.9	15.3	3A	26.2	17.7	3A	17.1	15.5
3B	17.5	16.6	3B	27.1	6.2	3B	25.4	8.5	3B	16.8	16.2
Average	17.04	26.76	Average	26.5	18.84	Average	26.4	19.1	Average	16.32	21.6
Date 21 NOVEMBER 1996			Date 7 JANUARY 1997			Date 19 FEBRUARY 1997			Date 16 APRIL 1997		
Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity
5	8.4	29.3	5	9.6	26.4	5	6.9	24.2	5	13.7	27.3
4	7.9	28.6	4	9.4	25.4	4	8.4	22.1	4	14.3	27.3
3	8	28.4	3	9.4	25.1	3	9.4	19	3	14.5	26.8
3A	8.1	27	3A	9.4	20.9	3A	11.1	14.7	3A	14.9	23.4
3B	8.1	14	3B	9.5	18.3	3B	13.5	7.2	3B	16.2	13.2
Average	8.1	25.46	Average	9.46	23.22	Average	9.86	17.44	Average	14.72	23.6

APPENDIX D.1 continued.

Date 14 MAY 1997			Date 30 JUNE 1997			Date 15 JULY 1997			Date 24 AUGUST 1997		
Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity
5	17.3	30.7	5	26.8	32.1	5	27.8	33.2	5	25.6	31.5
4	16.8	28.7	4	26.1	32.2	4	28.4	33.2	4	24.5	31.9
3	16.9	28.7	3	26.3	32.1	3	28.7	33.1	3	24.4	31.8
3A	16.8	26	3A	26.2	31.5	3A	29	31.4	3A	23.3	29.9
3B	16.9	14.5	3B	27.1	26.1	3B	29.4	27.2	3B	23.2	28.7
Average	16.94	25.72	Average	26.5	30.8	Average	28.66	31.62	Average	24.2	30.76
Date 25 SEPTEMBER 1997			Date 23 OCTOBER 1997			Date 12 NOVEMBER 1997			Date 9 DECEMBER 1997		
Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity	Station	Surface Temperature (C)	Surface Salinity
5	20.5	33.5	5	14.9	30.8	5	12.6	29.6	5	5.6	29.3
4	20	33.5	4	13.9	30.5	4	12.1	28.7	4	5.7	28.6
3	19.7	33.2	3	13.6	30.4	3	12.2	28.5	3	5.7	28.3
3A	19.4	32.4	3A	13.3	29.7	3A	12.2	27	3A	5.8	27.2
3B	18.5	24.9	3B	11.4	23.7	3B	12.5	14.3	3B	5.6	20.1
Average	19.62	31.5	Average	13.42	29.02	Average	12.32	25.62	Average	5.68	26.7

APPENDIX D.1 continued.

Date 7 FEBRUARY 1998			Date 22 MARCH 1998			Date 21 APRIL 1998			Date 23 MAY 1998		
Station	Surface Temp	Surface Temp(C)	Station	Surface Temp (C)	Surface Salinity	Station	Surface Temp (C)	Surface Salinity	Station	Surface Temp (C)	Surface Salinity
5	5.8	24.2	5	8.4	25.9	5	16.7	29.3	5	22.1	29.4
4	5.9	22.6	4	8	22.7	4	16.5	26.6	4	21.2	28.9
3	6	22.2	3	8	21.9	3	16.6	26.2	3	21.3	28.7
3A	6.3	19.8	3A	8.2	18.3	3A	16.5	20.4	3A	20.9	27.1
3B	6.7	13.7	3B	8.2	9.4	3B	16.9	17	3B	19	12
Average	6.14	20.5	Average	8.16	19.64	Average	16.64	23.9	Average	20.9	25.22

APPENDIX D.2

LIGHT DATA FOR GREENS CREEK

DATE: 29 MAY 1996															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	350.00	1.79	100.00	no data			160.00	1.39	100.00	240.00	1.68	100.00	205.00	1.28	100.00
0.50	163.00		46.57				99.00		61.88	108.00		45.00	65.00		31.71
1.00	62.00		17.71				36.00		22.50	41.00		17.08	30.00		14.63
1.50	21.60		6.17				20.00		12.50	21.00		8.75			
2.00	6.00		1.71							10.00		4.17			
2.50	4.00		1.14							3.60		1.50			
3.00										0.00		0.00			
DATE: 15 JULY 1996															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	315.00	1.75	100.00	no data			310.00	3.17	100.00	145.00	1.94	100.00	NO DATA		
0.50	85.00		26.98				32.00		10.32	33.00		22.76			
1.00	35.00		11.11				13.00		4.19	11.00		7.59			
1.50	15.00		4.76							3.00		2.07			
2.00	7.00		2.22												
2.50	4.00		1.27												
DATE: 7 AUGUST 1996															

APPENDIX D.2 continued.

0.00	375.00	2.15	100.00	no data			520.00	1.60	100.00	675.00	1.47	100.00	750.00	2.64	100.00
0.50	220.00		58.67				280.00		53.85	300.00		44.44	200.00		26.67
1.00	91.00		24.27				100.00		19.23	75.00		11.11			
1.50	15.00		4.00				47.00		9.04	36.00		5.33			
DATE: 7 JANUARY 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	225.00	1.12	100.00	375.00	0.96	100.00	375.00	1.30	100.00	220.00	1.08	100.00	600.00	1.08	100.00
0.50	130.00		57.78	190.00		50.67	170.00		45.33	130.00		59.09	350.00		58.33
1.00	80.00		35.56	110.00		29.33	80.00		21.33	65.00		29.55			
1.50	61.00		27.11	85.00		22.67	53.00		14.13	35.00		15.91			
2.00	24.00		10.67	55.00		14.67				24.00		10.91			
2.50										13.00		5.91			
3.00										8.50		3.86			
DATE: 19 FEBRUARY 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	650.00	1.19	100.00	800.00	1.34	100.00	800.00	1.46	100.00	800.00	1.58	100.00	800.00	1.96	100.00
0.50	350.00		53.85	450.00		56.25	350.00		43.75	280.00		35.00	300.00		37.50
1.00	200.00		30.77	230.00		28.75	150.00		18.75	80.00		10.00			
1.50	90.00		13.85	100.00		12.50	90.00		11.25	29.00		3.63			
2.00	60.00		9.23	55.00		6.88				15.00		1.88			
2.50										11.00		1.38			

APPENDIX D.2 continued.

3.00										7.00		0.88			
DATE: 4 APRIL 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	1250.00	0.92	100.00	1300.00	1.28	100.00	1200.00	1.42	100.00	1050.00	1.31	100.00	900.00	na	100.00
0.50	750.00		60.00	675.00		51.92	650.00		54.17	650.00		61.90			
1.00	500.00		40.00	340.00		26.15	300.00		25.00	270.00		25.71			
1.50	350.00		28.00	190.00		14.62	142.00		11.83	120.00		11.43			
2.00	200.00		16.00	100.00		7.69				66.00		6.29			
2.50										40.00		3.81			
DATE: 14 MAY 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	1100.00	1.03	100.00	600.00	0.98	100.00	600.00	0.88	100.00	680.00	1.47	100.00	750.00	1.02	100.00
0.50	750.00		68.18	410.00		68.33	410.00		68.33	450.00		66.18	450.00		
1.00	500.00		45.45	240.00		40.00	250.00		41.67	180.00		26.47			
1.50	300.00		27.27	120.00		20.00				75.00		11.03			
2.00	150.00		13.64	85.00		14.17									
2.50	100.00		9.09												
3.00	50.00		4.55												
DATE: 30 JUNE 1997															

APPENDIX D.2 continued.

DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	1100.00	2.43	100.00	1100.00	1.94	100.00	800.00	1.12	100.00	990.00	3.13	100.00	1100.00	2.60	100.00
0.50	600.00		54.55	600.00		54.55	490.00		61.25	160.00		16.16	300.00		27.27
1.00	90.00		8.18	160.00		14.55	260.00		32.50	45.00		4.55			
1.50	21.00		1.91	60.00		5.45				9.00		0.91			
2.00	2.50		0.23												
DATE: 15 JULY 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	1000.00	2.13	100.00	1000.00	1.55	100.00	1000.00	1.44	100.00	1000.00	2.34	100.00	1000.00	1.94	100.00
0.50	530.00		53.00	500.00		50.00	600.00			550.00		55.00	380.00		38.00
1.00	175.00		17.50	190.00		19.00	260.00			200.00		20.00			
1.50	30.00		3.00	98.00		9.80	115.00			30.00		3.00			
2.00	14.00		1.40												
DATE: 24 AUGUST 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	120.00	1.60	100.00	500.00	1.68	100.00	400.00	1.39	100.00	520.00	2.12	100.00	700.00	1.98	100.00
0.50	80.00		66.67	260.00		52.00	230.00		57.50	200.00		38.46	260.00		37.14
1.00	40.00		33.33	80.00		16.00	100.00		25.00	60.00		11.54			
1.50	11.00		9.17	40.00		8.00				19.00		3.65			
2.00	6.00		5.00							6.00		1.15			

APPENDIX D.2 continued.

2.50	1.50		1.25							1.50		0.29			
3.00	1.00		0.83							0.90		0.17			
DATE: 9 SEPTEMBER 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	102.00	1.17	100.00	164.50	0.88	100.00	137.67	0.74	100.00	149.96	1.57	100.00	268.60	1.63	100.00
0.50	56.98		55.86	114.78		69.78	100.21		72.79	78.49		52.34	118.20		44.01
1.00	32.99		32.34	70.89		43.09	65.67		47.70	33.87		22.59	52.71		19.62
1.50	17.26		16.92	43.86		26.66				15.39		10.26			
2.00	9.85		9.66							6.48		4.32			
DATE: 23 OCTOBER 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	451.70	1.34	100.00	452.90	1.48	100.00	486.00	1.20	100.00	656.70	1.61	100.00	634.20	2.15	100.00
0.50	322.70		71.44	337.70		74.56	363.10		74.71	447.30		68.11	222.00		35.00
1.00	143.30		31.72	85.76		18.94	156.80		32.26	154.60		23.54	74.23		11.70
1.50	63.47		14.05	49.41		10.91	80.63		16.59	63.47		9.66			
2.00	31.21		6.91							26.81		4.08			
2.50										10.15		1.55			
3.00										5.46		0.83			
3.50										2.03		0.31			
4.00										1.04		0.16			

APPENDIX D.2 continued.

DATE: 12 NOVEMBER 1997															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	470.00	1.74	100.00	415.00	0.87	100.00	524.00	0.92	100.00	325.00	1.03	100.00	432.00	2.77	100.00
0.50	240.00		51.06	295.00		71.08	307.00		58.59	213.00		65.54	108.00		25.00
1.00	101.00		21.49	183.00		44.10	209.00		39.89	124.00		38.15			
1.50	40.00		8.51	113.00		27.23				70.00		21.54			
2.00	17.00		3.62							43.00		13.23			
2.50	6.00		1.28							22.00		6.77			
3.00										15.00		4.62			
DATE: 7 FEBRUARY 1998															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	518.10	3.27	100.00	845.80	2.01	100.00	728.70	1.91	100.00	722.40	2.02	100.00	480.70	1.74	100.00
0.50	93.05		17.96	446.90		52.84	404.00		55.44	318.70		44.12	220.90		45.95
1.00	31.19		6.02	167.80		19.84	131.30		18.02	86.18		11.93	84.72		17.62
1.50	4.34		0.84	48.33		5.71	41.68		5.72	30.06		4.16			
2.00	0.75		0.14	16.57		1.96				11.13		1.54			
2.50				5.49		0.65				3.01		0.42			
3.00										1.68		0.23			
DATE: 22 MARCH 1998															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface

APPENDIX D.2 continued.

0.00	344.90	1.49	100.00	545.10	1.62	100.00	428.40	1.45	100.00	383.90	1.98	100.00	408.70	2.04	100.00
0.50	163.50			375.00		68.79	255.90		59.73	215.90		56.24	184.80		45.22
1.00				135.50		24.86	91.64		21.39	90.01		23.45	53.13		13.00
1.50				52.92		9.71	34.85		8.13	24.72		6.44			
2.00				19.48		3.57	23.66		5.52	11.32		2.95			
2.50				6.95		1.27				4.26		1.11			
3.00				4.27		0.78				1.01		0.26			
DATE: 21 APRIL 1998															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	2088.00	2.00	100.00	1997.00	0.95	100.00	1979.00	0.84	100.00	1935.00	3.23	100.00	19.48	na	100.00
0.50	1191.00		57.04	1290.00		64.60	1256.00		63.47	853.60		44.11			
1.00	631.10		30.23	771.50		38.63	815.90		41.23	458.60		23.70			
1.50	354.60		16.98				565.00		28.55	197.51		10.21			
2.00	191.60		9.18							98.00		5.06			
2.50	84.55		4.05							0.60		0.03			
3.00	49.48		2.37												
3.50	20.37		0.98												
4.00	0.71		0.03												
DATE: 23 MAY 1998															
DEPTH (m)	5	Att. Coeff.	% of surface	4	Att. Coeff.	% of surface	3	Att. Coeff.	% of surface	3A	Att. Coeff.	% of surface	3B	Att. Coeff.	% of surface
0.00	150.88	1.49	100.00	242.70	1.49	100.00	198.60	1.66	100.00	165.54	1.98	100.00	140.70	na	100.00

APPENDIX D.2 continued.

0.50	119.16		78.98	161.20		66.42	131.30		66.11	78.03		47.14			
1.00	42.16		27.94	59.55		24.54	37.95		19.11	21.69		13.10			
1.50	16.88		11.19	26.14		10.77				7.56		4.57			
2.00	7.66		5.08							2.70		1.63			
2.50										0.92		0.56			
3.00										0.44		0.27			
3.50										0.17		0.10			
4.00										0.06		0.04			

APPENDIX D.3

EASTERN SHORE LIGHT ATTENUATION COEFFICIENTS

							Photic Depth (1% light level)		
Sample Date	Station						Sample Date	Station	Station
	5	4	3	3A	3B			5	3
29-May-96	1.79	na	1.39	1.68	1.28		29-May-96	2.50	1.50
15-Jul-96	1.75	na	3.17	1.94	na		15-Jul-96	2.50	1.00
7-Aug-96	2.15	na	1.60	1.47	2.64		7-Aug-96	2.00	1.50
7-Jan-97	1.12	0.96	1.30	1.08	1.08		7-Jan-97	2.00	1.50
19-Feb-97	1.19	1.34	1.46	1.58	1.96		19-Feb-97	2.00	1.50
4-Apr-97	0.92	1.28	1.42	1.31	na		4-Apr-97	2.00	1.50
14-May-97	1.03	0.98	0.88	1.47	1.02		14-May-97	3.00	1.00
30-Jun-97	2.43	1.94	1.12	3.13	2.60		30-Jun-97	1.50	1.00
15-Jul-97	2.13	1.55	1.44	2.34	1.94		15-Jul-97	2.00	1.50
24-Aug-97	1.60	1.68	1.39	2.12	1.98		24-Aug-97	2.50	1.00
9-Sep-97	1.17	0.88	0.74	1.57	1.63		9-Sep-97	2.00	1.00
23-Oct-97	1.34	1.48	1.20	1.61	2.15		23-Oct-97	2.00	1.50
12-Nov-97	1.74	0.87	0.92	1.03	2.77		12-Nov-97	2.50	1.00
7-Feb-98	3.27	2.01	1.91	2.02	1.74		7-Feb-98	1.50	1.50
22-Mar-98	1.49	1.62	1.45	1.98	2.04		22-Mar-98	2.00	2.00
21-Apr-98	2.00	0.95	0.84	3.23	na		21-Apr-98	3.50	1.50
23-May-98	1.49	1.49	1.66	1.98	na		23-May-98	2.00	1.00
Average Attenuation Coeff.	1.68	1.36	1.40	1.86	1.91		Average Photic Depth	2.20	1.30
Max.	3.27	1.94	3.17	3.23	2.77		Max	3.50	2.00
Min.	0.92	0.87	0.74	1.03	1.02		Min	1.50	1.00

APPENDIX E.1

EASTERN SHORE CHLOROPHYLL DATA

DATE: May 29, 1996

STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	1.24	0.76	1.43	1.64	1.27	47.01
		1.37	0.80	1.68	1.70	1.18	41.33
		1.30	0.81	1.46	1.61	1.41	49.09
	<20	1.11	0.71	1.19	1.57	1.32	52.68
		0.71	0.46	0.75	1.55	0.87	53.76
		0.87	0.55	0.96	1.59	0.99	50.82
3	whole	1.63	0.98	1.93	1.66	1.55	44.59
		1.40	0.86	1.60	1.63	1.44	47.36
		1.26	0.75	1.50	1.68	1.17	43.71
	<20	1.42	0.87	1.63	1.63	1.46	47.16
		1.23	0.76	1.39	1.62	1.31	48.46
		1.40	0.85	1.63	1.65	1.38	45.92
3A	whole	3.47	1.96	4.47	1.77	2.49	35.80
		3.45	1.92	4.53	1.80	2.29	33.59
		3.31	1.83	4.38	1.81	2.12	32.60
	<20	4.02	2.17	5.48	1.85	2.23	28.96
		3.83	2.10	5.12	1.82	2.34	31.35
		3.20	1.76	4.26	1.82	1.99	31.82
3B	whole	5.67	3.32	6.96	1.71	4.84	41.01
		5.54	3.17	7.02	1.75	4.24	37.70
		6.11	3.52	7.67	1.74	4.84	38.68
	<20	4.73	2.81	5.68	1.68	4.30	43.06
		4.31	2.51	5.33	1.72	3.59	40.24
		5.46	3.13	6.90	1.74	4.22	37.97

APPENDIX E.1 continued.

DATE: July 15, 1996							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	3.15	1.72	4.23	1.83	1.88	30.72
		2.81	1.58	3.64	1.78	1.97	35.13
		2.82	1.59	3.64	1.77	2.01	35.53
	<20	2.27	1.34	2.75	1.69	2.01	42.16
		2.54	1.48	3.14	1.72	2.12	40.32
		2.30	1.34	2.84	1.72	1.92	40.30
3	whole	2.98	1.68	3.85	1.77	2.12	35.52
		3.14	1.77	4.06	1.77	2.23	35.50
		3.24	1.81	4.23	1.79	2.20	34.16
	<20	3.07	1.75	3.91	1.75	2.31	37.14
		2.82	1.60	3.61	1.76	2.07	36.46
		2.92	1.66	3.73	1.76	2.17	36.75
3A	whole	3.41	1.91	4.44	1.79	2.34	34.55
		4.95	2.73	6.57	1.81	3.13	32.23
		4.65	2.56	6.19	1.82	2.91	31.97
	<20	3.74	2.14	4.74	1.75	2.87	37.69
		4.17	2.40	5.24	1.74	3.29	38.54
		3.48	2.04	4.26	1.71	2.98	41.18
3B	whole	4.44	2.60	5.45	1.71	3.79	41.03
		4.77	2.79	5.86	1.71	4.05	40.86
		4.41	2.63	5.27	1.68	4.07	43.60
	<20	3.92	2.45	4.35	1.60	4.35	50.00
		3.93	2.44	4.41	1.61	4.26	49.11
		4.39	2.67	5.09	1.64	4.39	46.32
DATE: August 7, 1996							
STATION	SIZE	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-	% Degraded Pigment

APPENDIX E.1 continued.

	FRACTION					a (µg/L)	
5	whole	2.82	1.56	3.73	1.81	1.81	32.69
		3.10	1.75	4.00	1.77	2.22	35.71
		2.05	1.16	2.63	1.77	1.49	36.06
	<20	2.02	1.14	2.60	1.77	1.44	35.67
		1.93	1.11	2.43	1.74	1.52	38.44
		2.08	1.21	2.58	1.72	1.72	40.08
3	whole	3.16	1.77	4.11	1.79	2.17	34.56
		2.14	1.21	2.75	1.77	1.55	35.95
		2.43	1.37	3.14	1.77	1.73	35.52
	<20	2.01	1.20	2.40	1.68	1.86	43.75
		2.43	1.44	2.93	1.69	2.18	42.71
		1.98	1.16	2.43	1.71	1.69	41.09
3A	whole	6.33	3.26	9.09	1.94	2.49	21.52
		6.42	3.28	9.29	1.96	2.36	20.22
		7.24	3.70	10.48	1.96	2.66	20.27
	<20	4.97	2.61	6.99	1.90	2.29	24.65
		5.89	3.07	8.35	1.92	2.56	23.45
		4.41	2.32	6.19	1.90	2.05	24.93
3B	whole	4.88	2.90	5.86	1.68	4.44	43.10
		4.76	2.81	5.77	1.69	4.21	42.17
		4.94	2.97	5.83	1.66	4.72	44.73
	<20	2.08	1.31	2.28	1.59	2.37	51.02
		1.86	1.19	1.98	1.56	2.24	53.08
		3.63	2.27	4.03	1.60	4.04	50.07
DATE: October 22, 1996							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment

APPENDIX E.1 continued.

5	whole	1.74	0.98	2.24	1.77	1.26	35.98
		1.69	0.97	2.14	1.75	1.29	37.69
		1.70	0.96	2.19	1.77	1.21	35.61
	<20	1.50	0.87	1.88	1.73	1.19	38.82
		1.40	0.82	1.70	1.70	1.22	41.75
		1.29	0.74	1.63	1.75	0.99	37.67
3	whole	1.33	0.80	1.57	1.66	1.28	44.96
		1.28	0.75	1.57	1.70	1.10	41.30
		1.49	0.88	1.80	1.69	1.33	42.40
	<20	1.35	0.80	1.64	1.70	1.18	41.82
		1.29	0.77	1.55	1.68	1.18	43.18
		0.95	0.56	1.14	1.68	0.86	42.96
3A	whole	2.40	1.42	2.90	1.69	2.14	42.49
		2.28	1.34	2.78	1.70	1.98	41.54
		1.79	1.06	2.16	1.69	1.60	42.61
	<20	2.02	1.22	2.37	1.66	1.97	45.36
		1.92	1.16	2.25	1.66	1.87	45.40
		1.95	1.19	2.25	1.64	1.98	46.78
DATE: November 21, 1996							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	0.87	0.52	1.03	1.67	0.81	43.91
		0.97	0.58	1.16	1.68	0.89	43.43
		0.95	0.57	1.14	1.68	0.87	43.17
	<20	0.85	0.51	1.00	1.66	0.81	44.93
		0.78	0.47	0.92	1.66	0.76	45.27
		0.86	0.52	1.00	1.65	0.84	45.52
4	whole	0.63	0.40	0.69	1.58	0.73	51.46

APPENDIX E.1 continued.

		0.70	0.44	0.76	1.59	0.80	51.14
		0.64	0.40	0.70	1.59	0.73	50.99
	<20	0.57	0.36	0.63	1.59	0.65	50.93
		0.61	0.39	0.65	1.57	0.73	52.75
		0.61	0.39	0.65	1.57	0.72	52.29
3	whole	0.56	0.36	0.59	1.55	0.69	53.83
		0.53	0.34	0.55	1.54	0.67	55.18
		0.59	0.38	0.61	1.54	0.75	55.16
	<20	0.62	0.40	0.65	1.56	0.76	53.70
		0.56	0.36	0.57	1.54	0.71	55.22
		0.56	0.36	0.59	1.56	0.68	53.68
3A	whole	0.54	0.37	0.48	1.44	0.85	63.68
		0.60	0.43	0.51	1.40	1.03	67.01
		0.51	0.38	0.40	1.36	0.94	70.24
	<20	0.52	0.39	0.40	1.35	0.98	71.15
		0.52	0.38	0.41	1.36	0.94	69.74
		0.45	0.33	0.36	1.37	0.80	69.00
3B	whole	1.14	0.83	0.91	1.37	2.04	69.15
		1.08	0.79	0.86	1.37	1.95	69.41
		1.10	0.81	0.87	1.37	1.99	69.46
	<20	0.89	0.68	0.62	1.30	1.81	74.62
		0.90	0.69	0.61	1.30	1.83	74.93
		0.87	0.67	0.59	1.30	1.80	75.11
DATE: January 7, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	2.05	1.17	2.60	1.75	1.55	37.32
		2.15	1.25	2.65	1.72	1.79	40.27

APPENDIX E.1 continued.

		2.23	1.29	2.78	1.73	1.80	39.28
	<20	1.82	1.05	2.28	1.73	1.45	38.89
		1.74	1.01	2.16	1.72	1.43	39.77
		1.77	1.03	2.19	1.72	1.47	40.13
	<5	0.21	0.14	0.22	1.54	0.27	54.71
		1.14	0.73	1.22	1.56	1.37	53.02
		0.75	0.50	0.75	1.51	1.02	57.67
4	whole	1.23	0.72	1.51	1.71	1.05	41.17
		1.31	0.77	1.61	1.71	1.10	40.63
		1.31	0.75	1.65	1.74	1.03	38.55
	<20	1.12	0.67	1.33	1.67	1.05	44.24
		0.92	0.55	1.10	1.68	0.84	43.43
		0.99	0.59	1.18	1.68	0.92	43.60
3	whole	1.19	0.71	1.42	1.67	1.11	43.86
		1.10	0.67	1.28	1.65	1.09	46.11
		0.96	0.58	1.12	1.65	0.96	46.20
	<20	0.95	0.58	1.10	1.64	0.95	46.32
		1.08	0.66	1.26	1.65	1.08	46.14
		0.79	0.48	0.92	1.64	0.79	46.40
3A	whole	1.05	0.68	1.09	1.54	1.33	55.03
		1.03	0.67	1.07	1.54	1.31	55.22
		1.09	0.72	1.11	1.52	1.43	56.29
	<20	0.80	0.54	0.77	1.48	1.14	59.80
		0.88	0.60	0.83	1.46	1.32	61.44
		0.88	0.59	0.86	1.49	1.23	58.97
3B	whole	1.76	1.10	1.95	1.60	1.95	50.00
		1.63	1.02	1.81	1.60	1.82	50.16
		1.90	1.17	2.16	1.62	2.00	48.01
	<20	1.59	0.99	1.78	1.61	1.74	49.49

APPENDIX E.1 continued.

		1.64	1.01	1.86	1.62	1.72	48.02
		1.63	1.01	1.84	1.61	1.75	48.84
DATE: February 19, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole			VIAL BROKE			#VALUE!
		6.62	3.32	9.77	1.99	2.02	17.17
		7.53	3.79	11.07	1.99	2.39	17.77
	<20	4.41	2.26	6.36	1.95	1.66	20.72
		4.58	2.33	6.66	1.97	1.62	19.53
		4.51	2.31	6.51	1.95	1.69	20.63
	<5	2.33	1.22	3.29	1.91	1.05	24.18
		2.06	1.08	2.90	1.91	0.94	24.38
		2.23	1.15	3.20	1.94	0.89	21.74
4	whole	4.79	2.45	6.93	1.96	1.78	20.41
		4.91	2.54	7.02	1.93	2.01	22.24
		5.05	2.63	7.16	1.92	2.18	23.32
	<20	3.57	1.91	4.91	1.87	1.87	27.57
		2.91	1.56	4.00	1.87	1.55	27.88
		2.87	1.54	3.94	1.86	1.53	28.03
3	whole	3.74	2.01	5.12	1.86	2.02	28.28
		3.89	2.08	5.36	1.87	2.03	27.48
		3.54	1.90	4.85	1.86	1.89	28.07
	<20	2.26	1.25	2.99	1.81	1.45	32.67
		2.21	1.20	2.99	1.84	1.27	29.86
		2.20	1.24	2.84	1.77	1.56	35.48
3A	whole	5.64	3.09	7.55	1.83	3.43	31.23

APPENDIX E.1 continued.

		6.25	3.45	8.29	1.81	3.97	32.37
		5.12	2.86	6.69	1.79	3.47	34.15
	<20	2.69	1.61	3.20	1.67	2.52	44.10
		3.18	1.91	3.76	1.66	3.03	44.59
		2.64	1.57	3.17	1.68	2.41	43.21
3B	whole	1.85	1.28	1.69	1.45	2.86	62.89
		1.97	1.36	1.81	1.45	3.03	62.62
		2.07	1.39	2.01	1.49	2.92	59.23
	<20	1.61	1.16	1.33	1.39	2.79	67.67
		1.32	0.97	1.02	1.36	2.44	70.40
		1.37	1.00	1.10	1.37	2.46	69.17

DATE: April 16, 1997

STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	1.68	0.92	2.26	1.83	1.01	30.83
		1.89	1.03	2.55	1.82	1.11	30.42
		1.60	0.88	2.13	1.82	1.00	31.99
	<20	1.11	0.65	1.36	1.70	0.96	41.46
		0.87	0.51	1.07	1.71	0.73	40.50
		1.04	0.61	1.27	1.70	0.89	41.26
	<5	0.51	0.31	0.60	1.65	0.50	45.52
		0.43	0.26	0.50	1.64	0.44	46.77
		0.53	0.33	0.61	1.63	0.54	47.18
4	whole	1.65	0.98	1.99	1.69	1.48	42.74
		1.78	1.03	2.22	1.73	1.44	39.32
		1.99	1.17	2.43	1.70	1.73	41.60
	<20	1.56	0.94	1.84	1.66	1.50	44.89
		1.46	0.90	1.66	1.62	1.53	48.00

APPENDIX E.1 continued.

		1.29	0.78	1.52	1.66	1.25	45.16
3	whole	1.92	1.15	2.28	1.67	1.81	44.20
		1.79	1.05	2.19	1.70	1.54	41.27
		1.83	1.08	2.22	1.69	1.62	42.13
	<20	1.21	0.74	1.39	1.63	1.24	47.26
		1.41	0.86	1.63	1.64	1.42	46.55
		1.35	0.83	1.53	1.62	1.44	48.44
	<5	1.45	0.91	1.61	1.60	1.61	50.11
		1.10	0.69	1.21	1.59	1.24	50.68
		1.03	0.65	1.12	1.58	1.20	51.89
3A	whole	1.65	1.02	1.86	1.62	1.76	48.53
		1.40	0.87	1.57	1.61	1.53	49.39
		1.72	1.06	1.95	1.62	1.81	48.11
	<20	1.10	0.72	1.12	1.52	1.45	56.37
		1.17	0.77	1.17	1.51	1.58	57.36
		1.09	0.71	1.14	1.54	1.37	54.67
3B	whole	1.57	1.05	1.54	1.50	2.19	58.73
		1.45	0.98	1.39	1.48	2.10	60.29
		1.39	0.94	1.34	1.48	1.99	59.71
	<20	1.16	0.83	0.98	1.40	1.96	66.73
		1.09	0.79	0.89	1.38	1.91	68.21
		0.92	0.65	0.78	1.41	1.54	66.23

DATE: May 14, 1997

STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	1.12	0.64	1.42	1.74	0.86	37.73
		1.30	0.75	1.64	1.71	1.00	37.92
		1.19	0.70	1.46	1.71	1.02	41.06
	<20	1.05	0.61	1.30	1.72	0.87	40.13

APPENDIX E.1 continued.

		0.88	0.51	1.10	1.74	0.69	38.61
		0.84	0.50	1.03	1.70	0.73	41.58
	<5	0.71	0.42	0.84	1.67	0.66	44.12
		0.67	0.40	0.79	1.68	0.62	43.74
		0.70	0.42	0.82	1.66	0.67	45.11
4	whole	2.35	1.30	3.11	1.81	1.51	32.69
		2.28	1.23	3.11	1.85	1.26	28.86
		2.04	1.10	2.78	1.85	1.12	28.79
	<20	1.94	1.07	2.58	1.81	1.23	32.24
		2.12	1.16	2.84	1.83	1.28	31.03
		1.79	0.96	2.47	1.87	0.93	27.46
3	whole	2.09	1.16	2.75	1.80	1.37	33.19
		1.95	1.09	2.55	1.79	1.33	34.25
		1.94	1.06	2.60	1.83	1.16	30.82
	<20	1.92	1.08	2.49	1.78	1.35	35.19
		1.67	0.94	2.16	1.78	1.18	35.28
		1.49	0.82	1.98	1.81	0.94	32.10
	<5	1.13	0.68	1.34	1.67	1.06	44.03
		1.06	0.62	1.30	1.71	0.90	40.86
		1.08	0.64	1.31	1.69	0.96	42.27
3A	whole	1.53	0.90	1.87	1.70	1.33	41.51
		2.15	1.24	2.69	1.73	1.71	38.84
		1.93	1.13	2.37	1.71	1.65	41.00
	<20	1.93	1.10	2.46	1.75	1.45	37.12
		1.69	0.99	2.07	1.71	1.44	41.08
		1.81	1.04	2.28	1.74	1.41	38.30
3B	whole	1.74	1.10	1.89	1.58	2.01	51.52
		1.75	1.09	1.95	1.61	1.92	49.54
		1.81	1.12	2.04	1.62	1.94	48.66

APPENDIX E.1 continued.

	<20	1.46	0.94	1.55	1.56	1.79	53.62
		1.43	0.91	1.54	1.57	1.70	52.52
		1.52	0.97	1.64	1.57	1.79	52.21
DATE: June 30, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (μg/L)	Fb/Fa	Phaeopigment-a (μg/L.)	% Degraded Pigment
5	whole	2.64	1.55	3.23	1.67	2.28	41.40
		2.46	1.47	2.93	1.72	2.29	43.88
		2.25	1.31	2.78	1.72	1.87	40.20
	<20	2.66	1.57	3.23	1.69	2.35	42.14
		2.67	1.56	3.29	1.71	2.26	40.71
		2.46	1.47	2.93	1.67	2.29	43.88
	<5	3.05	1.76	3.82	1.73	2.43	38.92
		2.63	1.48	3.40	1.78	1.85	35.25
		2.96	1.66	3.85	1.78	2.05	34.74
4	whole	3.68	2.08	4.74	1.77	2.65	35.90
		3.14	1.77	4.06	1.77	2.23	35.50
		3.65	2.09	4.62	1.75	2.81	37.80
	<20	3.24	1.87	4.06	1.73	2.59	38.95
		2.78	1.60	3.49	1.74	2.19	38.54
		3.11	1.74	4.06	1.79	2.13	34.39
3	whole	4.29	2.43	5.51	1.77	3.13	36.21
		4.36	2.49	5.54	1.75	3.31	37.42
		3.79	2.14	4.88	1.77	2.72	35.75
	<20	3.22	1.86	4.03	1.73	2.58	39.07
		3.75	2.12	4.82	1.77	2.71	35.93
		3.92	2.20	5.09	1.78	2.72	34.85
	<5	3.33	1.93	4.14	1.73	2.71	39.55
		2.59	1.51	3.20	1.72	2.17	40.40

APPENDIX E.1 continued.

		3.14	1.82	3.91	1.73	2.56	39.56
3A	whole	7.75	4.24	10.39	1.83	4.67	31.01
		6.97	3.79	9.41	1.84	4.05	30.08
		7.60	4.41	9.44	1.72	6.22	39.72
	<20	6.33	3.49	8.41	1.81	3.99	32.19
		4.91	2.80	6.25	1.75	3.70	37.20
		5.44	3.04	7.10	1.79	3.69	34.21
3B	whole	6.90	3.75	9.32	1.84	4.00	30.00
		8.85	4.89	11.72	1.81	5.65	32.52
		8.59	4.74	11.40	1.81	5.44	32.31
	<20	6.04	3.47	7.61	1.74	4.72	38.28
		6.65	3.82	8.38	1.74	5.19	38.26
		5.49	3.14	6.96	1.75	4.20	37.63
DATE: July 15, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (μg/L)	Fb/Fa	Phaeopigment-a (μg/L)	% Degraded Pigment
5	whole	4.93	2.82	6.25	1.78	3.77	37.65
		4.12	2.32	5.33	1.74	2.91	35.34
		4.36	2.51	5.48	1.74	3.44	38.58
	<20	3.86	2.20	4.91	1.75	2.90	37.12
		4.03	2.32	5.06	1.74	3.18	38.58
		4.22	2.42	5.33	1.74	3.27	38.02
	<5	3.99	2.25	5.15	1.77	2.84	35.56
		3.56	2.04	4.50	1.75	2.75	37.91
		3.73	2.11	4.80	1.77	2.70	36.02
4	whole	5.84	3.16	7.93	1.85	3.29	29.32
		5.23	2.76	7.31	1.89	2.49	25.42
		5.04	2.71	6.90	1.86	2.73	28.35
	<20	3.93	2.18	5.18	1.80	2.56	33.10

APPENDIX E.1 continued.

		4.66	2.57	6.19	1.81	2.94	32.23
		4.94	2.68	6.69	1.84	2.83	29.73
3	whole	5.00	2.76	6.63	1.81	3.17	32.37
		5.37	2.94	7.19	1.83	3.25	31.12
		4.94	2.70	6.63	1.83	2.96	30.86
	<20	4.50	2.47	6.01	1.82	2.76	31.51
		4.02	2.21	5.36	1.82	2.49	31.75
		4.74	2.64	6.22	1.80	3.16	33.71
	<5	4.41	2.48	5.71	1.78	3.10	35.15
		4.35	2.45	5.62	1.78	3.08	35.37
		4.16	2.31	5.48	1.80	2.73	33.26
3A	whole	6.26	3.56	7.99	1.76	4.65	36.80
		6.16	3.47	7.96	1.78	4.36	35.40
		6.22	3.48	8.11	1.79	4.25	34.39
	<20	4.35	2.53	5.39	1.72	3.60	40.05
		5.29	3.03	6.69	1.75	4.07	37.84
		5.13	2.98	6.36	1.72	4.22	39.88
3B	whole	8.24	4.60	10.77	1.79	5.56	34.06
		8.17	4.54	10.74	1.80	5.38	33.37
		7.59	4.20	10.03	1.81	4.88	32.74
	<20	5.32	2.97	6.96	1.79	3.59	34.06
		5.45	3.12	6.90	1.75	4.19	37.77
		6.17	3.49	7.93	1.77	4.46	36.01
DATE: August 24, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	3.85	2.11	5.15	1.78	2.34	31.28
		3.94	2.21	5.12	1.80	2.73	34.77

APPENDIX E.1 continued.

		3.98	2.21	5.24	1.80	2.61	33.26
	<20	5.10	2.74	6.99	1.86	2.75	28.22
		4.90	2.66	6.63	1.84	2.82	29.82
		4.58	2.45	6.30	1.87	2.40	27.55
	<5	3.65	2.06	4.71	1.77	2.61	35.68
		2.93	1.63	3.85	1.80	1.94	33.54
		3.59	2.02	4.65	1.78	2.53	35.23
4	whole	3.37	1.86	4.47	1.81	2.14	32.35
		3.31	1.91	4.14	1.73	2.64	38.92
		3.45	1.95	4.44	1.77	2.49	35.90
	<20	2.68	1.52	3.43	1.76	1.97	36.40
		3.28	1.85	4.23	1.77	2.34	35.59
		2.52	1.43	3.23	1.76	1.85	36.48
3	whole	4.36	2.38	5.86	1.83	2.59	30.67
		4.44	2.42	5.98	1.83	2.62	30.44
		3.89	2.14	5.18	1.82	2.42	31.85
	<20	3.47	1.91	4.62	1.82	2.17	31.94
		3.75	2.08	4.94	1.80	2.44	33.09
		3.98	2.22	5.21	1.79	2.68	33.93
	<5	2.29	1.37	2.72	1.67	2.14	44.04
		2.16	1.30	2.55	1.66	2.07	44.87
3A	whole	7.66	4.16	10.36	1.84	4.42	29.89
		7.17	3.87	9.77	1.85	3.98	28.94
		6.38	3.48	8.58	1.83	3.78	30.56
	<20	6.12	3.38	8.11	1.81	3.90	32.45
		6.39	3.56	8.38	1.79	4.27	33.75
		5.65	3.15	7.40	1.79	3.79	33.86
3B	whole	6.28	3.56	8.05	1.76	4.59	36.33
		3.83	2.36	4.35	1.62	4.03	48.09

APPENDIX E.1 continued.

		5.67	3.24	7.19	1.75	4.32	37.50
	<20	4.09	2.51	4.68	1.63	4.24	47.54
		4.25	2.60	4.88	1.63	4.35	47.12
		4.21	2.60	4.77	1.62	4.47	48.40
DATE: September 25, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	2.03	1.10	2.75	1.86	1.15	29.55
		2.01	1.08	2.75	1.80	1.08	28.24
		1.69	0.94	2.22	1.80	1.11	33.35
	<20	0.73	0.46	0.82	1.61	0.80	49.49
		0.88	0.54	1.00	1.62	0.92	47.99
		0.86	0.53	0.97	1.62	0.90	48.23
	<5	1.23	0.74	1.46	1.67	1.15	44.07
		0.93	0.57	1.06	1.63	0.97	47.90
		0.83	0.52	0.91	1.60	0.92	50.19
4	whole	2.70	1.43	3.76	1.89	1.32	25.99
		2.49	1.32	3.46	1.89	1.23	26.14
		2.66	1.41	3.70	1.89	1.31	26.12
	<20	1.12	0.68	1.29	1.64	1.14	46.88
		1.14	0.69	1.35	1.66	1.09	44.65
		1.08	0.66	1.24	1.64	1.10	46.97
3	whole	1.52	0.90	1.84	1.69	1.35	42.28
		1.76	0.97	2.33	1.81	1.13	32.60
		2.00	1.11	2.63	1.80	1.31	33.18
	<20	1.34	0.84	1.48	1.60	1.50	50.40
		1.10	0.71	1.16	1.56	1.35	53.68
		1.07	0.65	1.24	1.65	1.07	46.15

APPENDIX E.1 continued.

	<5	SPILLED				na	na
		2.13	1.50	1.86	1.42	3.46	65.00
		2.07	1.46	1.81	1.42	3.38	65.18
3A	whole	8.83	4.64	12.40	1.90	4.08	24.75
		9.04	4.86	12.37	1.86	4.89	28.33
		8.95	4.80	12.28	1.86	4.77	27.95
	<20	6.98	3.80	9.41	1.84	4.08	30.26
		5.66	3.09	7.61	1.83	3.37	30.69
		7.26	3.85	10.09	1.89	3.58	26.19
3B	whole	3.99	2.48	4.47	1.61	4.34	49.26
		3.36	2.06	3.85	1.63	3.47	47.41
		3.47	2.19	3.79	1.58	3.99	51.29
	<20	2.02	1.36	1.95	1.49	2.88	59.56
		2.76	1.89	2.58	1.46	4.14	61.64
		2.77	1.89	2.60	1.47	4.11	61.20
DATE: October 23, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	0.79	0.50	0.86	1.58	0.93	52.03
		0.78	0.49	0.85	1.57	0.90	51.39
		0.90	0.57	0.97	1.57	1.07	52.38
	<20	0.67	0.44	0.69	1.53	0.87	55.86
		0.73	0.49	0.74	1.51	0.99	57.22
		0.65	0.43	0.64	1.50	0.90	58.53
	<5	0.61	0.41	0.59	1.49	0.87	59.44
		0.59	0.40	0.58	1.49	0.83	58.96
		0.36	0.24	0.36	1.50	0.49	57.99
4	whole	0.71	0.45	0.77	1.58	0.84	51.99

APPENDIX E.1 continued.

		0.72	0.46	0.76	1.56	0.87	53.34
		0.66	0.42	0.71	1.58	0.77	51.92
	<20	0.49	0.32	0.48	1.50	0.66	57.95
		0.54	0.36	0.53	1.50	0.76	58.68
		0.51	0.34	0.50	1.50	0.70	58.46
3	whole	0.71	0.48	0.69	1.49	1.00	59.29
		0.71	0.47	0.71	1.51	0.96	57.45
		0.81	0.54	0.80	1.50	1.11	58.10
	<20	0.72	0.49	0.66	1.45	1.10	62.55
		0.53	0.37	0.48	1.44	0.83	63.41
		0.63	0.42	0.61	1.49	0.89	59.22
	<5	0.56	0.40	0.47	1.40	0.95	67.08
		0.54	0.39	0.46	1.40	0.91	66.32
		0.49	0.35	0.41	1.40	0.84	66.95
3A	whole	1.64	1.00	1.90	1.64	1.64	46.39
		1.25	0.79	1.35	1.57	1.47	52.14
		1.03	0.66	1.11	1.57	1.22	52.49
	<20	0.92	0.63	0.84	1.45	1.40	62.49
		1.09	0.75	1.00	1.45	1.66	62.38
		0.77	0.52	0.74	1.49	1.09	59.39
3B	whole	1.87	1.47	1.18	1.27	4.04	77.32
		1.86	1.48	1.12	1.26	4.13	78.60
		1.55	1.20	1.04	1.29	3.23	75.69
	<20	1.15	0.93	0.67	1.24	2.62	79.73
		1.38	1.13	0.74	1.22	3.27	81.56
		1.53	1.26	0.80	1.21	3.68	82.14
DATE: November 12, 1997							
STATION	SIZE	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-	% Degraded Pigment

APPENDIX E.1 continued.

	FRACTION					a (µg/L)	
5	whole	0.66	0.45	0.65	1.47	0.93	58.99
		0.64	0.44	0.61	1.50	0.94	60.73
		0.82	0.55	0.82	1.50	1.13	57.95
	<20	0.67	0.45	0.65	1.49	0.95	59.54
		0.57	0.40	0.51	1.43	0.90	63.90
		0.55	0.38	0.52	1.47	0.82	61.21
	<5	0.60	0.40	0.58	1.49	0.84	59.16
		0.57	0.41	0.49	1.41	0.95	66.13
		0.61	0.43	0.54	1.42	0.99	64.84
4	whole	0.62	0.44	0.52	1.39	1.06	67.34
		0.59	0.42	0.51	1.41	0.98	65.59
		0.52	0.37	0.45	1.41	0.86	65.90
	<20	0.47	0.34	0.41	1.41	0.79	66.12
		0.52	0.37	0.44	1.41	0.86	65.85
		0.55	0.39	0.48	1.42	0.90	65.08
3	whole	0.50	0.36	0.44	1.41	0.83	65.59
		0.58	0.40	0.52	1.43	0.92	64.11
		0.52	0.37	0.44	1.40	0.87	66.71
	<20	0.45	0.32	0.38	1.39	0.77	67.13
		0.47	0.34	0.39	1.39	0.81	67.55
		VIAL BROKE					
	<5	0.40	0.29	0.32	1.38	0.69	68.24
		0.45	0.33	0.37	1.38	0.80	68.24
		0.49	0.36	0.39	1.37	0.89	69.53
3A	whole	0.69	0.48	0.63	1.44	1.07	63.02
		0.76	0.52	0.70	1.45	1.16	62.32
		0.91	0.63	0.82	1.44	1.40	63.05
	<20	0.59	0.43	0.47	1.37	1.06	69.21

APPENDIX E.1 continued.

		0.65	0.47	0.54	1.39	1.11	67.10
		0.63	0.46	0.51	1.38	1.13	68.73
3B	whole	1.33	1.03	0.89	1.29	2.77	75.73
		1.36	1.05	0.92	1.30	2.81	75.40
		1.39	1.09	0.89	1.28	2.98	77.06
	<20	1.28	1.05	0.68	1.22	3.05	81.75
		1.26	1.03	0.68	1.22	2.98	81.39
		1.31	1.06	0.74	1.24	3.03	80.35
DATE: December 9, 1997							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	1.32	0.67	1.93	1.88	0.45	18.91
		1.64	0.87	2.27	1.89	0.82	26.61
		1.51	0.80	2.10	1.89	0.73	25.84
	<20	0.98	0.54	1.30	1.81	0.62	32.22
		0.89	0.50	1.17	1.80	0.59	33.50
		0.95	0.53	1.25	1.80	0.63	33.68
	<5	0.77	0.45	0.97	1.74	0.61	38.71
		0.65	0.38	0.80	1.72	0.54	40.10
		0.84	0.48	1.05	1.73	0.67	38.92
4	whole	1.28	0.69	1.74	1.85	0.72	29.19
		1.33	0.72	1.81	1.85	0.75	29.18
		1.14	0.62	1.53	1.83	0.68	30.85
	<20	0.89	0.50	1.17	1.79	0.60	33.90
		0.94	0.52	1.23	1.80	0.63	33.68
		0.88	0.49	1.16	1.81	0.57	32.89
3	whole	1.46	0.79	1.97	1.84	0.85	30.10
		1.52	0.81	2.10	1.88	0.77	26.76

APPENDIX E.1 continued.

		1.49	0.80	2.06	1.87	0.77	27.15
	<20	1.22	0.67	1.63	1.83	0.74	31.14
		1.20	0.66	1.59	1.81	0.77	32.50
		1.04	0.58	1.36	1.80	0.69	33.65
	<5	0.78	0.45	0.96	1.71	0.66	40.71
		0.73	0.42	0.93	1.76	0.54	36.75
		0.85	0.49	1.06	1.73	0.69	39.44
3A	whole	1.20	0.69	1.52	1.75	0.91	37.35
		1.20	0.68	1.55	1.78	0.84	35.19
		1.12	0.64	1.41	1.74	0.87	38.18
	<20	1.01	0.60	1.22	1.69	0.90	42.59
		0.99	0.58	1.23	1.72	0.83	40.41
		0.84	0.50	1.02	1.69	0.75	42.49
3B	whole	1.02	0.66	1.06	1.54	1.30	55.13
		1.43	0.95	1.43	1.51	1.93	57.36
		1.56	1.02	1.60	1.53	2.02	55.88
	<20	1.32	0.87	1.34	1.52	1.73	56.31
		1.49	0.98	1.50	1.51	2.00	57.15
		1.30	0.88	1.26	1.48	1.86	59.67
DATE: February 7, 1998							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	5.76	3.26	7.40	1.75	4.18	36.09
		5.26	3.00	6.69	1.77	3.97	37.22
		5.89	3.33	7.58	1.77	4.25	35.94
	<20	2.37	1.52	2.52	1.56	2.88	53.40
		2.63	1.69	2.78	1.56	3.22	53.65
		1.78	1.14	1.89	1.56	2.15	53.22

APPENDIX E.1 continued.

	<5	0.49	0.32	0.49	1.52	0.65	56.65
		0.36	0.24	0.36	1.51	0.48	57.09
		0.51	0.34	0.51	1.51	0.69	57.35
4	whole	3.46	1.88	4.68	1.84	2.00	29.96
		3.31	1.85	4.32	1.79	2.25	34.23
		3.51	1.91	4.74	1.84	2.05	30.19
	<20	1.44	0.87	1.70	1.66	1.38	44.93
		1.63	1.00	1.87	1.63	1.67	47.23
		1.64	1.00	1.89	1.64	1.66	46.67
3	whole	3.47	1.90	4.65	1.83	2.10	31.14
		4.22	2.30	5.68	1.83	2.49	30.43
		3.60	1.99	4.77	1.81	2.30	32.58
	<20	2.24	1.37	2.58	1.64	2.29	47.08
		1.80	1.11	2.04	1.62	1.90	48.20
		2.34	1.42	2.72	1.65	2.32	46.01
	<5	0.47	0.30	0.49	1.55	0.59	54.50
		0.43	0.28	0.45	1.55	0.53	54.14
		0.44	0.28	0.47	1.57	0.52	52.51
3A	whole	2.65	1.50	3.40	1.77	1.92	36.11
		2.79	1.56	3.64	1.79	1.90	34.29
		2.52	1.43	3.23	1.76	1.85	36.48
	<20	1.22	0.76	1.35	1.60	1.36	50.09
		1.06	0.70	1.08	1.53	1.39	56.24
		1.14	0.71	1.28	1.61	1.24	49.34
3B	whole	1.79	1.09	2.07	1.64	1.80	46.48
		1.97	1.18	2.34	1.67	1.85	44.21
		1.81	1.09	2.13	1.66	1.74	44.95
	<20	1.70	1.05	1.92	1.62	1.81	48.41
		1.75	1.07	2.01	1.64	1.79	47.04

APPENDIX E.1 continued.

		1.62	0.99	1.87	1.64	1.64	46.69
DATE: March 22, 1998							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	1.84	1.05	2.34	1.75	1.39	37.30
		2.20	1.26	2.78	1.76	1.69	37.83
		1.92	1.09	2.46	1.76	1.41	36.54
	<20	1.57	0.93	1.89	1.69	1.42	42.80
		1.46	0.86	1.77	1.70	1.29	42.02
		1.57	0.93	1.90	1.69	1.39	42.20
	<5	1.34	0.78	1.65	1.71	1.13	40.54
		1.27	0.75	1.55	1.70	1.09	41.28
		1.32	0.77	1.64	1.72	1.09	39.92
4	whole	1.29	0.79	1.48	1.63	1.32	47.08
		1.11	0.69	1.24	1.60	1.22	49.66
		1.29	0.80	1.46	1.62	1.38	48.62
	<20	1.25	0.77	1.41	1.61	1.34	48.75
		1.19	0.76	1.28	1.57	1.41	52.33
		1.10	0.69	1.23	1.60	1.21	49.71
3	whole	1.12	0.69	1.28	1.63	1.15	47.28
		1.08	0.67	1.23	1.62	1.14	48.20
		1.29	0.80	1.45	1.61	1.39	48.96
	<20	1.43	0.90	1.56	1.58	1.65	51.37
		1.19	0.75	1.29	1.58	1.38	51.64
		1.23	0.78	1.33	1.57	1.45	52.26
	<5	1.22	0.77	1.32	1.58	1.42	51.81
		1.14	0.73	1.22	1.56	1.37	53.02
		1.28	0.82	1.38	1.57	1.52	52.45

APPENDIX E.1 continued.

3A	whole	1.54	0.95	1.75	1.62	1.63	48.25
		1.48	0.93	1.63	1.59	1.66	50.43
		1.49	0.94	1.64	1.59	1.68	50.68
	<20	1.40	0.88	1.55	1.60	1.57	50.30
		1.23	0.76	1.41	1.63	1.28	47.57
		1.19	0.73	1.36	1.63	1.23	47.49
3B	whole	0.92	0.64	0.82	1.43	1.46	63.99
		1.01	0.71	0.89	1.42	1.64	64.96
		0.97	0.66	0.92	1.47	1.43	60.98
	<20	0.95	0.66	0.86	1.44	1.48	63.33
		1.07	0.74	0.98	1.45	1.65	62.67
		1.12	0.78	1.02	1.44	1.74	63.21
	<5	1.00	0.70	0.88	1.42	1.61	64.69
		1.05	0.73	0.94	1.43	1.67	63.96
		1.04	0.73	0.91	1.42	1.69	64.94
DATE: April 21,1998							
STATION	SIZE FRACTION	Fb	Fa	Chl-a (µg/L)	Fb/Fa	Phaeopigment-a (µg/L)	% Degraded Pigment
5	whole	0.99	0.59	1.20	1.70	0.88	42.26
		1.13	0.67	1.38	1.67	0.99	41.73
		1.15	0.69	1.37	1.67	1.07	43.84
	<20	1.14	0.67	1.39	1.70	0.98	41.33
		1.11	0.66	1.32	1.67	1.03	43.82
		1.14	0.69	1.32	1.64	1.14	46.45
	<5	1.00	0.62	1.12	1.61	1.09	49.36
		0.81	0.48	0.97	1.69	0.73	42.82
		0.96	0.59	1.09	1.63	1.00	47.85
4	whole	1.15	0.71	1.31	1.62	1.21	48.17

APPENDIX E.1 continued.

		1.17	0.70	1.38	1.66	1.12	44.84
		1.33	0.79	1.59	1.68	1.23	43 57
	<20	0.97	0.59	1.13	1.65	0.95	45.72
		1.01	0.64	1.10	1.59	1.16	51.20
		1.05	0.65	1.18	1.61	1.13	48.92
3	whole	0.84	0.53	0.93	1.59	0.95	50.69
		1.13	0.68	1.33	1.66	1.10	45.26
		1.17	0.71	1.37	1.65	1.15	45.62
	<20	0.89	0.53	1.05	1.67	0.84	44.24
		0.77	0.46	0.91	1.67	0.73	44.56
		0.82	0.51	0.91	1.61	0.89	49.48
	<5	0.86	0.55	0.93	1.58	1.01	52.01
		0.80	0.52	0.84	1.55	1.00	54.38
		0.86	0.55	0.91	1.57	1.02	52.84
3A	whole	4.87	2.57	6.81	1.89	2.32	25.42
		3.42	1.86	4.62	1.84	1.99	30.11
		4.00	2.13	5.54	1.88	2.03	26.84
	<20	3.56	1.93	4.82	1.84	2.03	29.62
		2.52	1.43	3.23	1.76	1.85	36.48
		4.51	2.35	6.39	1.92	1.95	23.40
3B	whole	22.50	11.30	33.15	1.99	6.99	17.40
		18.10	9.02	26.88	2.01	5.16	16.11
		26.20	13.20	38.48	1.98	8.41	17.93
	<20	18.70	9.50	27.23	1.97	6.51	19.30
		18.60	9.60	26.64	1.94	7.46	21.87
		21.30	10.70	31.38	1.99	6.63	17.45
	<5	13.20	6.65	19.39	1.98	4.23	17.92
		12.80	6.25	19.39	2.05	2.81	12.67
		13.10	6.57	19.33	1.99	4.01	17.17

APPENDIX E.2

PHYTOPLANKTON CELL ENUMERATION

Sample Date	Station	Magnification	No. Fields	Cells Counted	Total Number of Cells (cells/L)
23-Oct-97	3	200X	9	9	53066
	3B	200X	9	22	129717
12-Nov-97	3	200X	9	15	88443
	3B	200X	9	72	424528
9-Dec-97	3	200X	9	12	70755
	3B	200X	9	8	47170
8-Feb-98	3	200X	9	50	294811
	3B	400X	9	92	3380775
22-Mar-98	3	200X	9	21	123821
	3B	400X	9	88	3233785
21-Apr-98	3	400X	9	49	1800630
	3B	200X	9	451	2659196
29-May-98	3	200X	9	43	253538
	3B	200X	5	107	1135612

APPENDIX E.3

PRIMARY PRODUCTION MODEL DATA

Production = phyto. biomass * photic depth * surface irradiance

Station 5							
	Total Chl-a	Total Chl-a	Photic Depth	Surface Irradiance	Surface Irradiance	Production	Production
Sample Date	(µg Chl-a /L)	(mg Chl-a / m)	(m)	(µE m-2 s-1)	(E m-2 day-1)	(mg C m-2 day-1	(g C m-2 year-1)
5/29/96	1.52	1.52	2.50	350	12.60	47.88	17.48
7/15/96	3.84	3.84	2.50	315	11.34	108.86	39.74
8/7/96	3.45	3.45	2.00	375	13.50	93.15	34.00
1/7/97	2.68	2.68	2.50	225	8.10	54.27	19.81
2/19/97	10.42	10.42	2.50	650	23.40	609.57	222.49
4/16/97	2.31	2.31	2.50	1250	45.00	259.88	94.85
5/14/97	1.51	1.51	3.50	1100	39.60	209.29	76.39
6/30/97	2.98	2.98	1.50	1100	39.60	177.01	64.61
7/15/97	5.68	5.68	2.00	1000	36.00	408.96	149.27
8/24/97	5.17	5.17	2.50	120	4.32	55.84	20.38
9/25/97	2.58	2.58	2.50	102	3.67	23.68	8.64
10/23/97	0.89	0.89	2.50	452	16.27	36.21	13.21
11/12/97	0.69	0.69	2.50	470	16.92	29.19	10.65
2/7/98	7.22	7.22	1.50	518	18.65	201.96	73.71
3/22/98	2.53	2.53	2.50	345	12.42	78.56	28.67
4/21/98	1.32	1.32	3.50	2088	75.17	347.28	126.76
mean	3.42	3.42	2.44	653.75	23.54	171.35	62.54
standard deviation	2.59	2.59	0.54	527.69	19.00	165.51	60.41
Station 3							
	Total Chl-a	Total Chl-a	Photic Depth	Surface Irradian	Surface Irradianc	Production	Production
Sample Date	(µg Chl-a /L	(mg Chl-a / m	(m)	(µE m-2 sec-1)	(E m-2 day-1)	(mg C m-2 day-1	(g C m-2 year-1)
5/29/96	1.68	1.68	1.50	350	12.60	31.75	11.59
7/15/96	4.05	4.05	1.00	310	11.16	45.20	16.50
8/7/96	3.33	3.33	1.50	520	18.72	93.51	34.13

APPENDIX E.3 continued.

1/7/97	1.27	1.27	1.50	375	13.50	25.72	9.39
2/19/97	5.11	5.11	1.50	800	28.80	220.75	80.57
4/16/97	2.23	2.23	1.50	1200	43.20	144.50	52.74
5/14/97	2.63	2.63	1.00	600	21.60	56.81	20.73
6/30/97	5.31	5.31	1.00	800	28.80	152.93	55.82
7/15/97	6.82	6.82	1.50	1000	36.00	368.28	134.42
8/24/97	5.67	5.67	1.00	400	14.40	81.65	29.80
9/25/97	2.27	2.27	1.00	138	4.97	11.28	4.12
10/23/97	0.74	0.74	1.50	486	17.50	19.42	7.09
11/12/97	0.46	0.46	1.00	524	18.86	8.68	3.17
2/7/98	5.03	5.03	1.50	728	26.21	197.74	72.17
3/22/98	1.32	1.32	2.00	428	15.41	40.68	14.85
4/21/98	1.21	1.21	1.50	1979	71.24	129.31	47.20
mean	3.07	3.07	1.34	664.88	23.94	101.76	37.14
standard deviation	2.01	2.01	0.30	443.93	15.98	97.76	35.68

APPENDIX F.1

ZOOPLANKTON TOW DATA

Net Size = 242um

Net Diameter = 0.5 meters

Tow Time = 2 minutes

Date	Tow No.	Flow Start	Flow Stop	Flow Count	Flow Volume (mL)	Split No.	# Animals/Split	Total Animals	Zoo. Volume (zoo/L)	Average Volume
9/25/97	1	730376	777264	46888	7803.20	4	16	128	16.40	16.40
10/23/97	1	177343	179095	1752	291.57	3	14	84	288.09	613.92
10/23/97	2	179092	180612	1520	252.96	4	25	200	790.63	
10/23/97	3	180610	182311	1701	283.08	2	54	216	763.02	
11/12/97	1	72232	182399	110167	18334.24	na				
11/12/97	2	182395	182770	375	62.41	3	15	90	1442.12	950.97
11/12/97	3	182770	184704	1934	321.86	2	37	148	459.83	
12/9/97	1	184495	187086	2591	431.20	3	46	276	640.07	646.59
12/9/97	2	187088	189566	2478	412.39	3	33	198	480.12	
12/9/97	3	189566	192440	2874	478.30	2	98	392	819.57	
2/8/98	1	82523	104795	22272	3706.56	7	136	1904	513.68	513.68
3/22/98	1	750412	753943	3531	587.64	7	705	9870	16796.09	10789.76
3/22/98	2	753943	756653	2710	451.00	9	361	6498	14407.85	
3/22/98	3	756653	792871	36218	6027.48	8	439	7024	1165.33	

APPENDIX F.1 continued.

4/21/98	1	168457	194950	26493	4409.02		empty	0	0	0.00	833.68
4/21/98	2	194950	198776	3826	636.73		5	109	1090	1711.87	
4/21/98	3	198776	211872	13096	2179.47		5	172	1720	789.18	
5/23/98	1	100000	102058	2058	342.50		3	141	846	2470.10	2078.72
5/23/98	2	102058	104252	2194	365.13		4	83	664	1818.53	
5/23/98	3	104252	106566	2314	385.10		3	125	750	1947.54	

APPENDIX G.1
PHYSICAL CALCULATIONS

$$\textbf{HTT (time)} = \frac{\Omega\ (m^3)}{Q\ (m^3\ time^{-1})}$$

$$Q\ (m^3\ time^{-1}) = V\ (m\ time^{-1}) * A\ (m^2)$$

a.) velocity for the ebb duration based on the 30 hour ADCP study

$D_1 = 30.97\ cm\ s^{-1}$

$D_2 = 26.15\ cm\ s^{-1}$

Mean velocity = $28.56\ cm\ s^{-1}$

b.) cross sectional area of the creek inlet (A) at high tide

Area = A_s = depth x width

Average Depth = 3.54 meters Width = approx. 30.1 meters

cross sectional area of the creek inlet (A) = $130.04\ m^2$

$$Q\ (m^3\ time^{-1}) = V\ (m\ time^{-1}) * A\ (m^2) = (0.2856\ m\ s^{-1})\ (130.04\ m^2)$$
$$= 37.14\ m^3\ s^{-1}$$

$$\text{CREEK } \Omega\ (m^3) = CSA(m^2) * L\ (m)$$

a.) cross sectional areas of the creek (CSA)

$CSA_1 = 154.9\ m^2$	$CSA_6 = 197.9\ m^2$
$CSA_2 = 191.3\ m^2$	$CSA_7 = 205.3\ m^2$
$CSA_3 = 197.0\ m^2$	$CSA_8 = 176.4\ m^2$
$CSA_4 = 171.4\ m^2$	$CSA_9 = 168.1\ m^2$
$CSA_5 = 201.2\ m^2$	$CSA_{10} = 157.6\ m^2$

APPENDIX G.1 continued.

Mean CSA = 182.1 m^2

b.) length of the creek = 3156 meters determined from a NOAA nautical chart

$$\Omega\ (m^3) = (\Omega_{wetland}) + (\Omega_{creek})$$

$\Omega\ (m^3)$ = (wetland area(m^2) * mean depth (m)) + (creek area(m^2) * length (m))

wetland area = approximately 150 hectares determined from a USGS Quad

mean water depth over wetland at high tide = 9 inches = 0.25 meters .

$\Omega_{wetland}$ = (150 ha) (0.25 m) = 0.375 (10^6) m^3

Ω_{creek} = CSA(m^2) * L (m) = (182.1 m^2) * (3156 m) = 0.575 (10^6) m^3

$\Omega\ (m^3) = (\Omega_{wetland}) + (\Omega_{creek})$ = 0.375 (10^6) m^3 + 0.575 (10^6) m^3 = 0.949 (10^6) m^3

HTT (time) = $\frac{\Omega\ (m^3)}{Q\ (M^3\ TIME^{-1})}$ = 0.949 (10^6) m^3 / 37.14 $m^3\ s^{-1}$ = 25,552 sec

HTT (TIME) = 7.1 HOURS

Estuary Number (e) = [Ω * (u_t)^2] / (g * h * Qf * Tt)

where Ω = tidal prism (volume) = 0.949 (10^6) m^3

u_t = time and depth averaged velocity of the tidal flow during the ebb duration = 0.2856 m s^{-1}

g = gravity constant (9.8 m s^{-2})

h = depth of the water column (m) = 3.54 m

Qf = F = 2.86 x 10^5 $m^3\ day^{-1}$ = 3.31 $m^3\ s^{-1}$

Qf = Vs (m $time^{-1}$)* As (m^2)

Spillway freshwater discharge = velocity x area of the spillway

Velocity ranged between 1.49 to 1.70 m s^{-1} with a mean velocity of 1.60 m s^{-1}

Area of the spillway: Area = 210.82 cm^2 = 2.12 m^2

Tt = tidal period = 6 hours

Estuary Number (e) = [Ω * (u_t)^2] / (g * h * Qf * Tt) Es = 0.029

APPENDIX G.2

30 HOUR ADCP STUDY

Greens Creek - ADCP 30 Hour Study	October 22-23,1996 Station #3

DATE	TIME	PRESSURE	TEMP	COND	HEADING	Y VELOCITY	X VELOCITY	SPEED	DIR.	SALINITY	SIGMA T
			(C)			cm/s	cm/s		degrees	ppt	
22-Oct-96	11:36:15	1.6	15.569	32.367	65.6	0.4	4.8	4.9	150.9	25.208	18.349
22-Oct-96	11:51:15	1.6	15.428	32.584	77.0	-1.6	1.1	2.0	223.0	25.485	18.591
22-Oct-96	12:06:15	1.6	15.493	32.622	75.3	-0.9	-0.2	0.9	268.0	25.477	18.571
22-Oct-96	12:21:14	1.6	15.469	32.527	95.5	-0.8	-2.9	3.0	350.1	25.409	18.524
22-Oct-96	12:36:14	1.6	16.144	32.538	61.8	0.6	-3.5	3.5	342.2	24.991	18.062
22-Oct-96	12:51:14	1.6	15.787	31.851	44.4	5.9	-6.0	8.4	359.0	24.628	17.859
22-Oct-96	13:06:14 PM	1.6	16.057	32.360	49.1	11.4	-8.3	14.2	12.9	24.894	18.006
22-Oct-96	13:21:14 PM	1.6	16.050	32.272	40.0	10.6	-11.7	15.8	352.3	24.824	17.954
22-Oct-96	13:36:14 PM	1.6	15.999	32.435	47.8	12.5	-9.8	15.9	9.8	24.995	18.095
22-Oct-96	13:51:14 PM	1.6	16.021	32.656	57.2	8.3	-9.4	12.5	8.5	25.168	18.224
22-Oct-96	14:06:13 PM	1.6	16.069	32.884	45.8	14.7	-7.6	16.6	18.6	25.332	18.339
22-Oct-96	14:21:13 PM	1.6	16.113	33.298	39.5	16.9	-14.6	22.3	358.6	25.657	18.579
22-Oct-96	14:36:13 PM	1.6	16.214	33.560	53.0	14.6	-12.2	19.0	13.0	25.815	18.678
22-Oct-96	14:51:13 PM	1.6	16.129	33.883	55.9	13.0	-18.6	22.7	0.8	26.145	18.949
22-Oct-96	15:06:13 PM	1.6	16.008	34.540	65.4	15.0	-29.3	32.9	2.6	26.789	19.468
22-Oct-96	15:21:13 PM	1.6	16.098	35.284	58.4	20.4	-32.5	38.3	0.5	27.368	19.894
22-Oct-96	15:36:13 PM	1.6	16.090	35.687	66.9	22.1	-36.1	42.3	8.4	27.719	20.163
22-Oct-96	15:51:13 PM	1.6	16.084	35.888	69.7	14.2	-36.2	38.9	1.1	27.897	20.301
22-Oct-96	16:06:12 PM	1.6	16.208	36.233	82.4	5.9	-45.2	45.6	359.8	28.107	20.435
22-Oct-96	16:21:12 PM	1.6	16.247	36.492	89.0	14.9	-77.6	79.0	9.9	28.302	20.576

APPENDIX G.2 continued.

22-Oct-96	16:36:12 PM	1.7	16.186	36.469	94.5	-0.3	-50.2	50.2	4.1	28.325	20.608
22-Oct-96	16:51:12 PM	1.7	16.192	36.518	101.6	0.5	-45.9	45.9	12.2	28.364	20.636
22-Oct-96	17:06:12 PM	1.7	16.214	36.545	91.8	3.0	-51.3	51.4	5.2	28.371	20.637
22-Oct-96	17:21:12 PM	1.7	16.183	36.484	99.9	1.3	-64.2	64.2	11.1	28.341	20.621
22-Oct-96	17:36:12 PM	1.7	16.188	36.560	88.4	4.2	-28.2	28.5	6.9	28.403	20.667
22-Oct-96	17:51:12 PM	1.7	16.174	36.553	109.0	3.2	-34.3	34.4	24.3	28.406	20.672
22-Oct-96	18:06:11 PM	1.6	16.163	36.560	99.5	2.3	-23.9	24.0	15.0	28.420	20.686
22-Oct-96	18:21:11 PM	1.6	16.171	36.568	95.3	6.4	-6.3	9.0	50.6	28.422	20.685
22-Oct-96	18:36:11 PM	1.6	16.171	36.560	355.5	-9.6	-0.2	9.6	176.6	28.415	20.680
22-Oct-96	18:51:11 PM	1.7	16.188	36.530	255.0	-5.6	-33.3	33.8	155.5	28.376	20.646
22-Oct-96	19:06:11 PM	1.7	16.200	36.515	266.5	-9.4	-43.9	44.9	164.4	28.355	20.647
22-Oct-96	19:21:11 PM	1.7	16.264	36.431	261.4	-10.4	-45.2	46.4	158.5	28.238	20.524
22-Oct-96	19:36:11 PM	1.7	16.240	36.393	253.8	-4.3	-55.3	55.5	159.4	28.222	20.517
22-Oct-96	19:51:10 PM	1.7	16.275	36.351	254.1	-3.7	-64.3	64.4	160.8	28.161	20.463
22-Oct-96	20:06:10 PM	1.7	16.268	36.264	246.1	6.6	-67.1	67.5	161.7	28.091	20.410
22-Oct-96	20:21:10 PM	1.7	16.288	36.047	249.8	6.9	-52.6	53.0	167.3	27.891	20.253
22-Oct-96	20:36:10 PM	1.6	16.297	35.770	239.8	14.6	-59.2	61.0	163.6	27.647	20.064
22-Oct-96	20:51:10 PM	1.6	16.325	35.368	233.9	18.6	-61.4	64.2	160.7	27.283	19.778
22-Oct-96	21:06:10 PM	1.6	16.340	35.071	218.3	36.3	-42.8	56.1	168.6	27.020	19.574
22-Oct-96	21:21:10 PM	1.6	16.354	34.783	215.6	34.7	-37.3	50.9	168.5	26.764	19.375
22-Oct-96	21:36:10 PM	1.6	16.374	34.574	217.3	32.0	-42.2	53.0	164.5	26.573	19.224
22-Oct-96	21:51:09 PM	1.6	16.392	34.342	216.3	26.0	-25.9	36.7	171.7	26.364	19.060
22-Oct-96	22:06:09 PM	1.6	16.402	34.133	215.7	20.5	-21.4	29.6	169.4	26.180	18.917
22-Oct-96	22:21:09 PM	1.6	16.409	33.985	211.7	18.1	-14.5	23.2	173.0	26.050	18.816
22-Oct-96	22:36:09 PM	1.6	16.417	33.867	207.8	13.8	-4.8	14.6	188.8	25.945	18.734
22-Oct-96	22:51:09 PM	1.6	16.426	33.788	192.0	10.1	-0.9	10.2	186.9	25.871	18.676
22-Oct-96	23:06:09 PM	1.6	16.432	33.734	195.2	12.4	-3.9	13.0	177.7	25.822	18.637
22-Oct-96	23:21:09 PM	1.6	16.440	33.693	200.1	10.6	-1.2	10.7	193.7	25.782	18.604
22-Oct-96	23:36:09 PM	1.6	16.446	33.617	204.4	8.7	-1.4	8.9	195.4	25.714	18.550
22-Oct-96	23:51:08 PM	1.6	16.434	33.510	203.6	7.3	0.0	7.3	203.8	25.631	18.490

APPENDIX G.2 continued.

23-Oct-96	0:06:08	1.6	16.428	33.491	182.2	4.1	0.5	4.1	189.4	25.619	18.482
23-Oct-96	0:21:08	1.6	16.462	33.734	182.4	3.5	1.1	3.6	199.9	25.803	18.616
23-Oct-96	0:36:08	1.6	16.465	33.765	132.9	3.0	1.1	3.2	153.9	25.827	18.633
23-Oct-96	0:51:08	1.6	16.452	33.750	97.6	1.1	-1.5	1.9	43.4	25.823	18.633
23-Oct-96	1:06:08	1.6	16.300	33.184	70.6	0.6	-0.2	0.6	55.8	25.441	18.373
23-Oct-96	1:21:08	1.6	16.214	32.891	63.9	2.4	1.3	2.8	92.0	25.247	18.243
23-Oct-96	1:36:07	1.6	16.167	32.641	67.4	1.8	-6.8	7.0	352.4	25.064	18.113
23-Oct-96	1:51:07	1.6	16.108	32.603	72.0	4.2	-14.6	15.2	358.2	25.068	18.129
23-Oct-96	2:06:07	1.6	16.089	32.671	61.0	10.1	-18.7	21.2	359.3	25.139	18.187
23-Oct-96	2:21:07	1.6	16.113	32.956	73.3	10.7	-17.4	20.5	14.8	25.366	18.356
23-Oct-96	2:36:07	1.6	16.121	33.187	75.5	9.2	-18.2	20.4	12.4	25.558	18.501
23-Oct-96	2:51:07	1.6	16.142	33.582	70.3	7.5	-8.9	11.7	20.4	25.881	18.744
23-Oct-96	3:06:07	1.6	16.179	33.826	83.1	5.4	-19.9	20.7	8.4	26.064	18.876
23-Oct-96	3:21:07	1.6	16.288	34.384	78.8	5.1	-24.4	24.9	0.7	26.469	19.163
23-Oct-96	3:36:06	1.6	16.307	34.695	90.5	1.6	-18.3	18.4	5.6	26.721	19.352
23-Oct-96	3:51:06	1.6	16.294	35.349	102.1	0.2	-32.5	32.5	12.4	27.288	19.798
23-Oct-96	4:06:06	1.6	16.268	35.736	74.0	13.2	-34.9	37.3	4.7	27.638	20.063
23-Oct-96	4:21:06	1.6	16.253	36.059	94.2	2.6	-62.2	62.2	6.6	27.925	20.286
23-Oct-96	4:36:06	1.6	16.242	36.146	91.4	13.7	-46.3	48.2	17.8	28.008	20.353
23-Oct-96	4:51:06	1.7	16.230	36.416	105.4	1.2	-64.0	64.0	16.4	28.249	20.540
23-Oct-96	5:06:06	1.7	16.204	36.492	110.9	-1.0	-58.3	58.3	19.9	28.333	20.609
23-Oct-96	5:21:05	1.7	16.176	36.530	98.6	-1.5	-65.3	65.3	7.3	28.385	20.656
23-Oct-96	5:36:05	1.7	16.158	36.590	104.8	-1.9	-55.7	55.8	12.9	28.451	20.710
23-Oct-96	5:51:05	1.7	16.139	36.602	96.9	2.1	-35.4	35.4	10.3	28.474	20.732
23-Oct-96	6:06:05	1.7	16.116	36.606	108.3	-3.0	-55.7	55.8	15.2	28.493	20.752
23-Oct-96	6:21:05	1.7	16.097	36.598	99.2	1.1	-27.3	27.9	11.5	28.501	20.762
23-Oct-96	6:36:05	1.6	16.086	36.583	104.3	-3.8	-21.0	21.4	3.9	28.495	20.760
23-Oct-96	6:51:05	1.6	16.081	36.583	141.9	0.7	0.7	0.9	187.0	28.499	20.763
23-Oct-96	7:06:05	1.6	16.019	36.469	219.3	10.8	-11.8	15.9	171.8	28.445	20.736
23-Oct-96	7:21:04	1.6	16.082	36.545	235.1	6.9	-36.4	37.1	155.8	28.465	20.738

APPENDIX G.2 continued.

23-Oct-96	7:36:04	1.6	16.059	36.370	238.0	5.1	-52.4	52.6	153.5	28.331	20.639
23-Oct-96	7:51:04	1.6	16.040	36.207	250.6	0.5	-44.8	44.8	161.2	28.203	20.546
23-Oct-96	8:06:04	1.6	16.046	36.260	237.2	22.2	-65.3	68.9	166.0	28.245	20.576
23-Oct-96	8:21:04	1.7	16.066	36.203	247.2	7.0	-63.9	64.3	163.5	28.182	20.524
23-Oct-96	8:36:04	1.6	16.062	36.025	238.4	15.5	-58.1	60.1	163.3	28.030	20.408
23-Oct-96	8:51:04	1.7	16.081	35.789	213.9	42.6	-56.1	70.4	161.1	27.813	20.238
23-Oct-96	9:06:04	1.6	16.090	35.318	204.3	52.8	-36.1	64.0	169.9	27.402	19.920
23-Oct-96	9:21:03	1.6	16.106	35.159	212.3	42.7	-42.7	60.3	167.3	27.254	19.804
23-Oct-96	9:36:03	1.6	16.140	34.893	210.9	44.7	-47.5	65.2	164.2	27.002	19.604
23-Oct-96	9:51:03	1.6	16.185	34.726	213.3	41.1	-40.8	57.9	168.5	26.829	19.461
23-Oct-96	10:06:03	1.6	16.246	34.505	215.6	29.3	-36.2	46.6	164.5	26.600	19.272
23-Oct-96	10:21:03	1.6	16.317	34.395	215.3	21.1	-30.7	37.2	159.8	26.459	19.149
23-Oct-96	10:36:03	1.6	16.382	34.270	210.1	22.5	-21.1	30.8	167.0	26.309	19.020
23-Oct-96	10:51:03	1.6	16.451	34.171	201.1	20.9	-9.2	22.9	177.3	26.180	18.907
23-Oct-96	11:06:02	1.6	16.530	34.126	166.7	19.3	2.6	19.5	174.2	26.090	18.820
23-Oct-96	11:21:02	1.6	16.605	34.091	128.8	8.5	10.2	13.3	179.0	26.012	18.744
23-Oct-96	11:36:02	1.6	16.751	34.129	76.5	-3.6	12.2	12.7	182.9	25.950	18.665
23-Oct-96	11:51:02	1.6	16.900	34.167	78.3	-3.3	13.1	13.5	182.5	25.886	18.583
23-Oct-96	12:06:02	1.6	17.027	34.175	69.9	-4.2	8.8	9.8	185.1	25.811	18.498
23-Oct-96	12:21:02	1.6	17.128	34.164	66.5	-1.2	8.8	8.9	164.4	25.738	18.419
23-Oct-96	12:36:02	1.6	17.289	34.259	60.5	-0.4	3.8	3.8	157.2	25.714	18.365
23-Oct-96	12:51:02	1.6	17.242	34.357	50.3	-1.8	2.7	3.2	174.0	25.826	18.461
23-Oct-96	13:06:01 PM	1.6	17.285	34.353	56.9	1.3	1.4	1.9	104.3	25.796	18.428
23-Oct-96	13:21:01 PM	1.6	17.313	34.338	65.3	1.2	0.7	1.4	96.2	25.765	18.399
23-Oct-96	13:36:01 PM	1.6	17.329	34.099	58.9	-0.1	-2.3	2.3	625.6	25.557	18.236
23-Oct-96	13:51:01 PM	1.6	17.156	33.765	61.1	0.5	-3.6	3.6	338.3	25.388	18.145
23-Oct-96	14:06:01 PM	1.6	17.044	33.469	59.5	8.4	-11.6	14.3	5.4	25.211	18.035
23-Oct-96	14:21:01 PM	1.6	17.036	33.374	61.3	11.1	-15.0	18.6	7.8	25.137	17.981
23-Oct-96	14:36:01 PM	1.6	16.996	33.362	61.1	8.0	-16.5	18.3	357.0	25.152	18.001
23-Oct-96	14:51:01 PM	1.6	16.947	33.548	65.6	10.3	-13.7	17.1	12.5	25.338	18.154

APPENDIX H.1

GREENS CREEK WATER QUALITY DATA

DATE: MAY 29, 1996 (RAINY EPISODE)										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	1.971	1.344	63.636	63.49	1.847	1.845	0.548	0.538	9.254	6.168
	0.717		63.337		1.842		0.528		3.083	
3	0.269	0.314	62.737	63.09	0.827	0.83	0.487	0.487	4.688	4.62
	0.358		63.437		0.832		0.487		4.552	
3A	0.134	0.762	68.032	68.58	0.582	0.594	0.508	0.508	5.96	6.199
	1.389		69.131		0.606		0.508		6.437	
3B	2.016	2.061	84.316	83.82	0.298	0.305	0.954	0.964	41.642	48.333
	2.106		83.317		0.313		0.974		55.024	
DATE: July 15, 1996										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	9.224	8.131	81.959	83.44	1.691	1.686	0.63	0.61	7.831	5.191
	7.039		84.916		1.681		0.59		2.551	
3	9.588	8.974	94.34	92.77	1.42	1.41	0.692	0.702	3.4	3.652
	8.36		91.199		1.401		0.712		3.903	
3A	7.886	8.508	103.95	104.2	1.438	1.436	0.773	0.773	8.545	8.996
	9.131		104.504		1.434		0.773		9.447	
3B	10.257	8.368	116.609	117.3	1.919	1.952	1.161	1.171	19.751	20.429

APPENDIX H.1 continued.

	6.48		117.902		1.985		1.181		21.108	
DATE: August 7, 1996 (DRY EPISODE)										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	5.909	5.087	62.127	62.02	1.494	1.514	0.914	0.924	9.071	6.187
	4.264		61.912		1.535		0.934		3.303	
3	5.65	5.331	83.372	82.25	1.591	1.62	0.853	0.863	5.711	6.01
	5.011		81.119		1.648		0.873		6.308	
3A	4.615	4.066	78.007	78.01	1.174	1.179	1.34	1.35	15.536	16.975
	3.518		78.007		1.185		1.36		18.414	
3B	4.828	5.292	59.552	59.71	1.756	1.761	1.38	1.38	48.841	50.551
	5.757		59.873		1.766		1.38		52.261	
R	3.153	3.29	26.396	26.77	0.881	0.886	0.528	0.538	39.425	39.462
	3.427		27.147		0.891		0.548		39.5	
DATE: OCTOBER 22, 1996										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	2.798	2.729	17.302	17.3	0.522	0.522	0.222	0.222	2.21	2.098
	2.661		17.302		0.522		0.222		1.987	
3	2.935	2.756	28.092	28.05	0.733	0.733	0.345	0.345	1.008	1.063
	2.578		27.999		0.733		0.345		1.119	
3A	2.551	2.14	26.883	26.74	0.416	0.416	0.386	0.396	9.348	9.489

APPENDIX H.1 continued.

	1.729		26.604		0.416		0.406		9.629	
R	0.62	0.62	30.565	30.84	0.15	0.15	1.153	1.153	130.245	130.25
	0.62		31.119		0.15		1.153		130.245	
DATE: NOVEMBER 21, 1996										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	2.017	2.565	21.86	22.14	0.627	0.627	0.222	0.212	na	na
	3.113		22.418		0.627		0.202		na	
4	1.249	1.626	19.72	19.86	0.627	0.627	0.202	0.202	na	na
	2.003		19.999		0.627		0.202		na	
3	2.798	2.654	21.488	21.49	0.574	0.574	0.243	0.243	na	na
	2.51		21.488		0.574		0.243		na	
3A	1.14	2.01	22.976	23.3	0.522	0.522	0.202	0.222	na	na
	2.88		23.627		0.522		0.243		na	
3B	3.099	3.147	13.953	14.09	0.311	0.311	0.141	0.151	na	na
	3.195		14.232		0.311		0.161		na	
R	3.524	3.359	28.929	28.6	0.258	0.232	0.406	0.406	na	na
	3.195		28.278		0.206		0.406		na	
DATE: JANUARY 7,										

APPENDIX H.1 continued.

1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	1.639	1.618	23.075	23.08	0.936	0.912	0.281	0.332	10.774	8.024
	1.596		23.075		0.888		0.383		5.274	
4	1.682	1.586	15.383	15.38	0.839	0.839	0.117	0.127	2.584	2.166
	1.489		15.383		0.839		0.137		1.748	
3	1.318	1.308	30.217	30.22	0.839	0.839	0.178	0.209	2.676	2.772
	1.297		30.217		0.839		0.24		2.869	
3A	1.725	1.703	53.017	53.02	0.936	0.936	0.322	0.312	14.655	15.684
	1.682		53.017		0.936		0.301		16.712	
3B	1.939	1.95	76.367	76.37	0.936	0.936	0.383	0.404	32.419	33.443
	1.96		76.367		0.936		0.424		34.467	
R	1.088	0.907	94.187	92.8	0.1	0.125	1.557	1.557	80.877	80.877
	0.726		91.417		0.15		1.557		80.877	
DATE: FEBRUARY 19, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	1.382	1.415	17.306	17.31	0.694	0.694	0.117	0.137	4.931	4.939
	1.447		17.306		0.694		0.158		4.947	

APPENDIX H.1 continued.

4	1.233	1.254	45.6	45.6	1.033	1.057	0.281	0.281	8.184	8.153
	1.275		45.6		1.082		0.281		8.122	
3	1.126	1.136	61.258	61.26	1.033	1.057	0.301	0.301	13.036	13.067
	1.147		61.258		1.082		0.301		13.098	
3A	1.725	1.714	75.268	75.27	1.179	1.251	0.527	0.537	26.657	26.583
	1.703		75.268		1.324		0.547		26.509	
3B	3.587	3.629	112.352	112.4	1.47	1.445	0.629	0.629	42.542	42.573
	3.672		112.352		1.421		0.629		42.604	
R	0.705	0.694	43.492	42.89	0.2	0.2	0.232	0.232	60.229	60.229
	0.684		42.292		0.2		0.232		60.229	
DATE: APRIL 16, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	2.559	2.581	23.075	23.08	1.033	1.057	0.076	0.076	3.286	1.87
	2.602		23.075		1.082		0.076		0.455	
4	2.238	2.206	38.733	38.73	1.033	1.033	0.199	0.199	1.106	1.85
	2.174		38.733		1.033		0.199		2.594	
3	1.554	1.543	29.393	29.39	0.985	1.057	0.24	0.25	2.787	3.067
	1.532		29.393		1.13		0.26		3.347	
3A	1.468	1.468	48.347	48.35	0.936	0.96	0.547	0.445	5.068	9.398
	1.468		48.347		0.985		0.342		13.727	

APPENDIX H.1 continued.

3B	2.559	2.602	85.432	85.43	1.13	1.203	0.527	0.506	37.288	44.423
	2.645		85.432		1.276		0.486		51.559	
R	0.471	0.513	114.409	114.4	0.1	0.1	0.793	0.793	100.827	100.83
	0.556		114.317		0.1		0.793		100.827	
DATE: June 30, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	1.318	1.329	67.576	67.58	2.003	2.003	0.035	0.035	3.961	3.898
	1.34		67.576		2.003		0.035		3.836	
4	1.254	1.265	78.839	78.84	1.906	1.882	0.014	0.014	3.921	3.984
	1.275		78.839		1.858		0.014		4.046	
3	1.061	1.061	84.608	84.61	1.761	1.761	0.014	0.014	3.984	3.984
	1.061		84.608		1.761		0.014		3.984	
3A	0.912	0.922	78.564	78.56	1.615	1.615	-0.027	-0.027	5.342	5.249
	0.933		78.564		1.615		-0.027		5.155	
3B	1.489	1.554	118.67	118.7	1.567	1.542	0.445	0.465	21.25	21.258
	1.618		118.67		1.518		0.486		21.266	
R	1.478	1.422	168.941	168.9	0.791	0.791	0.465	0.465	142.82	142.87
	1.366		168.941		0.791		0.465		142.911	
DATE: JULY 15, 1997										

APPENDIX H.1 continued.

NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	1.233	1.233	67.576	67.58	2.149	2.149	0.076	0.066	3.665	3.707
	1.233		67.576		2.149		0.055		3.75	
4	1.425	1.436	93.398	93.4	2.246	2.27	0.014	0.035	3.671	3.68
	1.447		93.398		2.294		0.055		3.688	
3	1.297	1.297	125.813	125.8	2.052	2.1	0.014	0.014	3.609	3.578
	1.297		125.813		2.149		0.014		3.546	
3A	0.976	0.965	176.357	176.4	1.761	1.736	-0.027	-0.027	3.405	3.467
	0.954		176.357		1.712		-0.027		3.53	
3B	2.495	2.41	215.365	215.4	1.809	1.809	0.301	0.322	15.723	15.825
	2.324		215.365		1.809		0.342		15.927	
R	1.322	1.322	99.991	99.99	0.742	0.742	0.465	0.455	133.547	133.52
	1.322		99.991		0.742		0.445		133.484	
DATE; AUGUST 24, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	3.009	2.987	120.868	120.9	2.003	2.221	0.609	0.65	5.128	5.05
	2.966		120.868		2.44		0.691		4.973	
4	2.538	2.559	108.781	108.8	2.197	2.221	0.363	0.383	4.467	4.475

APPENDIX H.1 continued.

	2.581		108.781		2.246		0.404		4.483	
3	2.452	2.42	96.145	96.15	2.149	2.173	0.301	0.301	4.223	4.223
	2.388		96.145		2.197		0.301		4.223	
3A	2.88	2.741	94.497	94.5	1.955	1.979	0.301	0.322	6.786	6.7
	2.602		94.497		2.003		0.342		6.615	
3B	6.839	7.76	193.389	193.4	1.858	1.858	0.793	0.814	39.42	39.334
	8.68		193.389		1.858		0.834		39.249	
R	2.464	2.464	134.603	134.6	0.791	0.791	0.588	0.599	155.743	155.73
	2.464		134.603		0.791		0.609		155.715	
DATE: SEPTEMBER 25, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	3.9911	3.991	136.801	136.8	6.008	6.008	1.726	1.726	2.996	3.027
	3.9911		136.801		6.008		1.726		3.058	
4	3.0281	3.028	114.001	114	7.589	7.589	1.834	1.834	2.562	2.624
	3.0281		114.001		7.589		1.834		2.687	
3	4.8257	4.826	127.186	127.2	7.028	7.028	2.395	2.395	1.805	1.805
	4.8257		127.186		7.028		2.395		1.805	
3A	2.7499	2.75	157.403	157.4	7.742	7.742	2.547	2.547	2.135	2.198
	2.7499		157.403		7.742		2.547		2.26	
3B	5.1681	5.168	228.001	228	6.773	6.773	2.136	2.136	34.659	34.597

APPENDIX H.1 continued.

	5.1681		228.001		6.773		2.136		34.534	
R	6.2381	6.238	280.743	280.7	0.041	0.041	1.791	1.791	129.798	129.89
	6.2381		280.743		0.041		1.791		129.986	
DATE: OCTOBER 23, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	2.8355	2.836	151.634	151.6	5.09	5.09	1.942	1.942	2.315	2.315
	2.8355		151.634		5.09		1.942		2.315	
4	3.5203	3.52	156.579	156.6	4.886	4.886	0.343	0.343	4.051	4.02
	3.5203		156.579		4.886		0.343		3.989	
3	3.1993	3.199	157.678	157.7	6.926	6.926	1.661	1.661	2.506	2.506
	3.1993		157.678		6.926		1.661		2.506	
3A	3.1993	3.199	163.721	163.7	5.651	5.651	0.84	0.84	4.43	4.367
	3.1993		163.721		5.651		0.84		4.305	
3B	4.3335	4.334	209.047	209	4.529	4.529	2.201	2.201	48.836	48.774
	4.3335		209.047		4.529		2.201		48.711	
R	4.1409	4.141	243.384	243.4	3.713	3.713	0.538	0.538	128.207	128.24
	4.1409		243.384		3.713		0.538		128.27	
DATE: NOVEMBER										

APPENDIX H.1 continued.

12, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	1.45152	1.452	22.8344	22.83	3.739	3.739	0.5964	0.596	2.12	2.12
	1.45152		22.8344		3.739		0.5964		2.12	
4	0.91392	0.914	21.0358	21.04	3.664	3.664	0.4899	0.49	2.081	2.062
	0.91392		21.0358		3.664		0.4899		2.042	
3	0.70272	0.703	22.1306	22.13	3.918	3.918	0.4686	0.469	1.965	1.965
	0.70272		22.1306		3.918		0.4686		1.965	
3A	0.74112	0.741	32.062	32.06	3.739	3.739	0.426	0.426	2.698	2.736
	0.74112		32.062		3.739		0.426		2.775	
3B	2.20032	2.2	43.9484	43.95	4.106	4.106	0.639	0.639	24.78	24.741
	2.20032		43.9484		4.106		0.639		24.703	
R	0.72192	0.722	53.7234	53.72	3.363	3.363	0.7668	0.767	70.87	70.793
	0.72192		53.7234		3.363		0.7668		70.716	
DATE: DECEMBER 9, 1997										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	0.20352	0.204	10.7134	10.71	3.044	3.044	0.3408	0.341	1.233	1.233
	0.20352		10.7134		3.044		0.3408		1.233	

APPENDIX H.1 continued.

4	0.22272	0.223	12.512	12.51	3.401	3.401	0.213	0.213	1.503	1.522
	0.22272		12.512		3.401		0.213		1.542	
3	0.22272	0.223	22.3652	22.37	3.457	3.457	0.1917	0.192	2.389	2.351
	0.22272		22.3652		3.457		0.1917		2.312	
3A	0.29952	0.3	14.2324	14.23	3.636	3.636	0.1917	0.192	2.852	2.852
	0.29952		14.2324		3.636		0.1917		2.852	
3B	0.68352	0.684	22.2088	22.21	4.031	4.031	0.2982	0.298	16.263	16.321
	0.68352		22.2088		4.031		0.2982		16.378	
R	0.81792	0.818	18.8462	18.85	2.846	2.846	0.3621	0.362	79.58	79.561
	0.81792		18.8462		2.846		0.3621		79.541	
DATE: FEBRUARY 7,1998										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	0.43392	0.434	7.1944	7.194	2.658	2.658	0.213	0.213	6.674	6.411
	0.43392		7.1944		2.658		0.213		6.148	
4	0.41472	0.415	11.73	11.73	2.574	2.574	0.1917	0.192	5.638	5.638
	0.41472		11.73		2.574		0.1917		5.638	
3	0.41472	0.415	12.903	12.9	2.611	2.611	0.1917	0.192	14.586	14.586
	0.41472		12.903		2.611		0.1917		14.586	
3A	0.37632	0.376	15.4054	15.41	2.781	2.781	0.213	0.213	32.99	32.727
	0.37632		15.4054		2.781		0.213		32.463	

APPENDIX H.1 continued.

3B	0.56832	0.568	12.0428	12.04	2.339	2.339	0.2982	0.298	103.975	104.24
	0.56832		12.0428		2.339		0.2982		104.501	
R	0.54912	0.549	5.7086	5.709	1.38	1.38	0.3195	0.32	147.116	147.12
	0.54912		5.7086		1.38		0.3195		147.116	
DATE; MARCH 22,1998										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	0.74112	0.741	11.2608	11.26	2.762	2.762	0.2982	0.298	27.659	27.659
	0.74112		11.2608		2.762		0.2982		27.659	
4	0.52992	0.53	9.9314	9.931	2.828	2.828	0.2556	0.256	30.851	30.588
	0.52992		9.9314		2.828		0.2556		30.325	
3	0.52992	0.53	13.8414	13.84	2.837	2.837	0.2769	0.277	15.571	15.308
	0.52992		13.8414		2.837		0.2769		15.045	
3A	0.47232	0.472	12.7466	12.75	2.818	2.818	0.3195	0.32	46.274	45.379
	0.47232		12.7466		2.818		0.3195		44.485	
3B	1.02912	1.029	13.2158	13.22	2.64	2.64	0.5112	0.511	171.702	171.7
	1.02912		13.2158		2.64		0.5112		171.702	
R	1.06752	1.068	10.6352	10.64	1.643	1.643	0.4899	0.49	204.876	204.88
	1.06752		10.6352		1.643		0.4899		204.876	
DATE:										

APPENDIX H.1 continued.

APRIL 21,1998										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	0.76032	0.76	25.2586	25.26	3.692	3.692	0.3834	0.383	6.013	6.013
	0.76032		25.2586		3.692		0.3834		6.013	
4	0.58752	0.588	27.6046	27.61	3.777	3.777	0.2982	0.298	18.712	18.449
	0.58752		27.6046		3.777		0.2982		18.186	
3	0.54912	0.549	30.5762	30.58	3.777	3.777	0.2982	0.298	23.975	25.028
	0.54912		30.5762		3.777		0.2982		26.08	
3A	0.35712	0.357	33.0004	33	3.401	3.401	0.9798	0.98	30.805	30.279
	0.35712		33.0004		3.401		0.9798		29.753	
3B	2.27712	2.277	70.3018	70.3	3.373	3.373	0.5751	0.575	416.914	415.86
	2.27712		70.3018		3.373		0.5751		414.809	
R	0.77952	0.78	34.408	34.41	1.982	1.982	0.3834	0.383	477.592	477.59
	0.77952		34.408		1.982		0.3834		477.592	
DATE: MAY 23,1998										
NUTRIENT	AMMONIA		SILICATE		PHOSPHATE		NITRITE		NITRATE	
STAT	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)	µM	X (µM)
5	0.74112	0.741	29.4032	29.4	3.636	3.636	0.3195	0.32	1.853	2.116
	0.74112		29.4032		3.636		0.3195		2.379	

APPENDIX H.1 continued.

4	0.95232	0.952	29.6378	29.64	3.598	3.598	0.2769	0.277	2.413	2.413
	0.95232		29.6378		3.598		0.2769		2.413	
3	0.87552	0.876	29.7942	29.79	3.335	3.335	0.213	0.213	3.516	3.779
	0.87552		29.7942		3.335		0.213		4.042	
3A	0.89472	0.895	36.6758	36.68	3.598	3.598	0.3408	0.341	23.941	24.468
	0.89472		36.6758		3.598		0.3408		24.994	
3B	4.38912	4.389	53.0978	53.1	3.796	3.796	1.0437	1.044	200.755	201.81
	4.38912		53.0978		3.796		1.0437		202.86	
R	1.33632	1.336	39.9602	39.96	2.517	2.517	0.4686	0.469	706.472	706.21
	1.33632		39.9602		2.517		0.4686		705.946	

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Education

BS, Chemical Oceanography, 1993
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Honors

Hampton Roads Maritime Scholar 1996-97, 1997-98

Grants

Co-principal Investigator: Groundwater Analysis
Part of technical support team for multi-disciplinary Eastern Shore Sustainable Agriculture Research and Education (SARE) grant project awarded to The Nature Conservancy by the U.S. Department of Agriculture (1996-1999).

Professional Experience

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Systems Operator Analyst: Baker GeoResearch, a Unit of Michael Baker Corporation.
Graduate Research Assistant - Old Dominion University, Dept. of Oceanography.
Onshore Pond Production Manager - Caicos Conch Farm, Turks and Caicos Islands, BWI.
Water Quality Analyst – Duda Aquaculture Farm, Cocoa, Florida.

Presentations

Dunstan, William M. and C.L. Lajoie. 1996. *Preliminary Observations on the Variability of Chlorophyll in the Machipongo Watershed and Hog Island Bay.* 2nd Eastern Shore Natural Resources Symposium. Cape Charles, Virginia. (author only)

Lajoie, Claudette and W.M. Dunstan. 1996. *Impacts of External Nutrient Loading on the Water Column Dynamics of a Coastal Watershed.* Southeastern Estuarine Research Society. Atlantic Beach, North Carolina. (presenter)

Dunstan, William M. and C.L. Lajoie. 1997. *Greens Creek: An overview.* Eastern Shore Water Quality Consortium. The Nature Conservancy, Brownsfield, Virginia. (presenter)

Lajoie, Claudette and W.M. Dunstan. 1997. *Biological factors influencing the behavior of dissolved nutrients in a coastal creek.* Southeastern Estuarine Research Society. Islamorada, Florida. (Presenter)

Lajoie Jenkins, Claudette and W.M. Dunstan. 1997. *Biological factors influencing the behavior of dissolved nutrients in a coastal creek.* Estuarine Research Federation: International State of Our Estuaries Symposium. Providence, Rhode Island (poster presentation)

Dunstan, William M. and C.L. Jenkins. 1997. Chlorophyll variability in a dynamic coastal watershed. Estuarine Research Federation: International State of Our Estuaries Symposium. Providence, Rhode Island. (author only)

Lajoie Jenkins, Claudette and W.M. Dunstan. 1999. The Impacts of External Nutrient Sources on Marine Phytoplankton in an Eastern Shore Sea-Side Estuary. SEERS. Jacksonville, FL.